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Ergonomic Design of a Vacuum Lift Assist End Effector for Handling Automotive Exhaust Systems

Independent Project – ACMA6013

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Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:



Date:

30/05/26

Acknowledgements

I would like to begin by thanking Tenneco for providing me with the opportunity and support to further my studies in Manufacturing Engineering. Having the opportunity to undertake this project on a real-world manufacturing challenge has been both rewarding and fulfilling, and I hope that the outcomes of this work will make a positive contribution to the business.

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Abstract

Manual handling operations on Robot 31 at Tenneco Highpoint were identified as a significant ergonomic and operational concern following a change of process for handling P6 MHEV automotive exhaust systems. The revised process required a two-person lift, increasing cycle time from 212 s to 227 s and introducing Health and Safety Executive (HSE) red-category manual handling risks. This project aimed to design, develop, and validate a bespoke vacuum lift-assist end effector capable of safely handling the exhaust assembly while maintaining production efficiency and integrating with existing vacuum lifting infrastructure.

A structured mechanical design methodology was employed, incorporating Quality Function Deployment (QFD), Design Failure Mode and Effects Analysis (DFMEA), concept generation and selection, material and manufacturing process evaluation, three-dimensional CAD modelling, finite element analysis (FEA), ergonomic assessment, and business case analysis. The final design utilised dual vacuum suction cups, a pivot mechanism with viscous damping, a welded steel frame, and adjustable support features to accommodate product variation and operator requirements.

Design verification demonstrated compliance with the majority of Product Design Specification (PDS) requirements. The final end-effector achieved a mass below the 18 kg target, maintained dimensional constraints, and provided a suction cup area of 654 cm² compared with the minimum requirement of 631 cm². FEA predicted a maximum structural stress of 51.1 MPa and maximum displacement of 2.2 mm, both within acceptable limits. Ergonomic assessments confirmed substantial reductions in manual handling risk and improved operator posture.

A business case review projected annual savings of approximately £85,000 through the elimination of overtime and additional labour requirements. The design achieved a predicted payback period of 1.25 months and received formal approval from the Tenneco senior management team to proceed to manufacture.

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Glossary of Terms

Abbreviation	Definition
AIAG	Automotive Industry Action Group
CAD	Computer-Aided Design
CFRP	Carbon Fibre Reinforced Polymer
CoG	Centre of Gravity
DFMEA	Design Failure Mode and Effects Analysis
EPDM	Ethylene Propylene Diene Monomer
FEA	Finite Element Analysis
FoS	Factor of Safety
HSE	Health and Safety Executive
HMI	Human-Machine Interface
ISO	International Organisation for Standardisation
MIG	Metal Inert Gas (Welding Process)
MHEV	Mild Hybrid Electric Vehicle
PDS	Product Design Specification
PPH	Parts Per Hour
PSA	Pressure Sensitive Adhesive
PVC	Polyvinyl Chloride
QFD	Quality Function Deployment
REBA	Rapid Entire Body Assessment
RPN	Risk Priority Number
ROI	Return on Investment
SWL	Safe Working Load
TIG	Tungsten Inert Gas (Welding Process)
VDI	Association of German Engineers
VOC	Voice of the Customer
WMSD	Work-Related Musculoskeletal Disorder

1. Introduction

1.1. Background to Tenneco

Tenneco-Walker (U.K.) Limited is a subsidiary of Tenneco, a world-leading Tier 1 Automotive component supplier with over 60,000 team members across 223 sites in 28 countries worldwide (Figure 2, Tenneco, 2025). It supplies major global vehicle manufacturers with products in areas such as emissions control systems, ride performance, powertrain components, and aftermarket solutions; examples of these products are shown in Figure 1 (MOOG, 2025; Tenneco, 2025b).



Figure 1: Examples of products manufactured by Tenneco (MOOG, 2025; Tenneco, 2025)



Figure 2: Tenneco Global Site Locations (Tenneco, 2025a).

As a Tier 1 supplier, Tenneco delivers directly to original equipment manufacturers (OEMs), including Ford, BMW, and Jaguar Land Rover, thereby playing a critical role in the global automotive supply chain. Tenneco's origins date back to 1930, when the

Chicago Corporation investment trust was formed. Since then, numerous mergers and acquisitions have occurred, and the company is now managed by Apollo Global Management, an asset management firm.

Tenneco-Walker (U.K.) Limited is based in Merthyr Tydfil, South Wales, and forms part of Tenneco's Clean Air division, manufacturing exhaust systems for the Light Vehicle sector. Its primary customer is the luxury vehicle manufacturer Jaguar Land Rover, for which it produces various exhaust assemblies.

Figure 3 (Kothari Suvrat, 2023) illustrates the tail trims of an L461 P6 PHEV exhaust system as an example of one such product. The manufacturing site is colloquially known as Highpoint, due to its location situated 400 m above sea level. From this point onwards, the site will be referred to as Highpoint.



Figure 3: 2023 Range Rover Sport (Kothari Suvrat, 2023)

Highpoint employs over 200 people and operates on a three-shift pattern from Monday to Friday. On average, the site produces 4,500 finished exhaust assemblies each week. The plant's core competency lies in joining operations, particularly MIG (Metal

Inert Gas) welding. Figure 4 illustrates an example of these capabilities, showing how raw components - including bent pipework, pressed baffles, and case sheets - are received from sub-suppliers and subsequently welded together to produce a rear muffler box assembly.

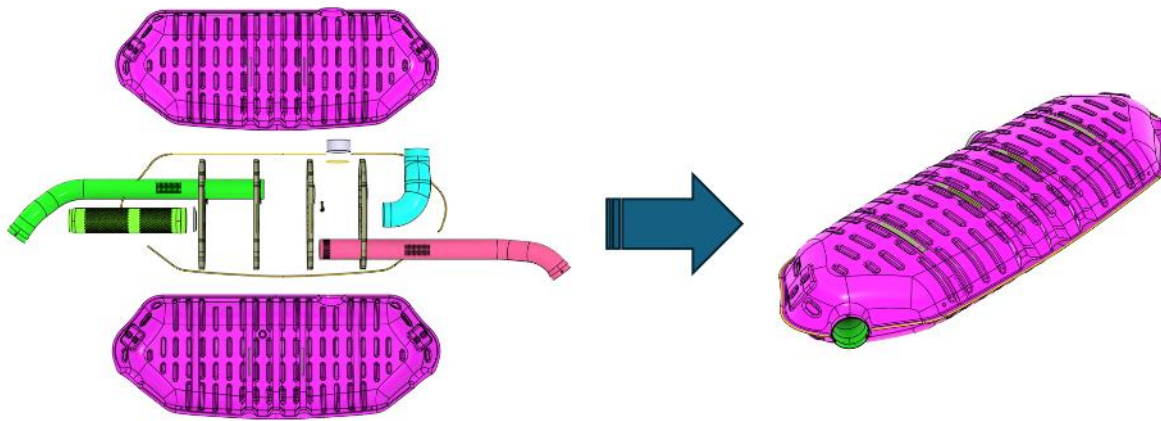


Figure 4: P6 MHEV Rear Muffler Box Assembly.

1.2. Problem Definition

The L460 and L461 Range Rover platform is the highest-volume platform in Highpoint's product portfolio, with an average weekly requirement of 3,200 units. On this platform, the P6 MHEV Cold End variant accounts for 50% of the total L460/L461 output, corresponding to an average weekly requirement of 1,600 units (Figure 6). The P6 MHEV Cold End consists of three sub-variants: L460 SWB, L460 LWB, and L461. The L461 variant, displayed in Figure 5, is the heaviest system, weighing 26.35 Kg. The largest system is the L460 LWB, measuring 3.21 m long and 1.35 m wide.

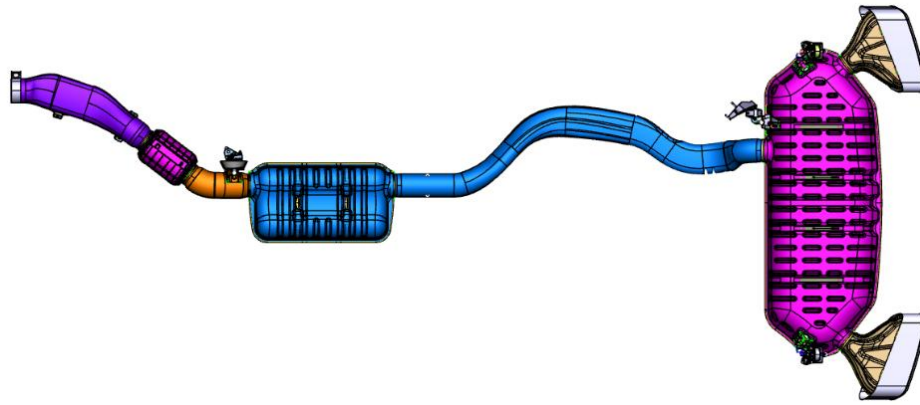


Figure 5: L461 P6 MHEV Cold End Exhaust.

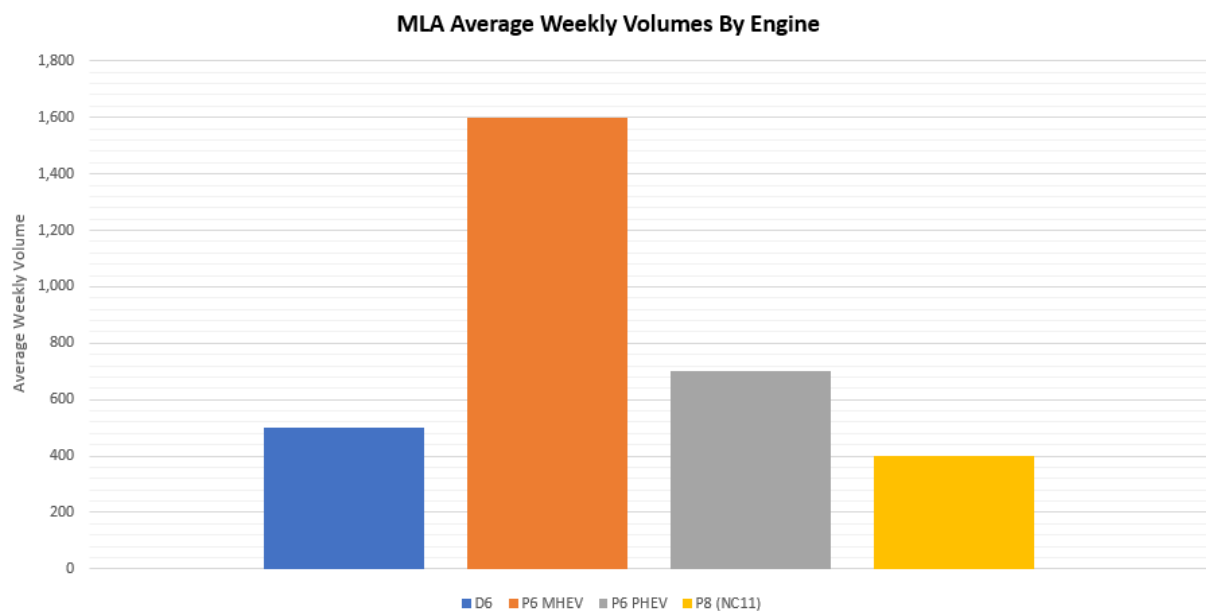


Figure 6: MLA Cold End Average Weekly Volumes

The final assembly operation of the P6 MHEV exhaust system is performed on Robot 31 and comprises several stages: robotic welding, visual inspection, manual rework, geometric inspection, leak testing, and packaging. The process flow between these operations is illustrated in Figure 7.

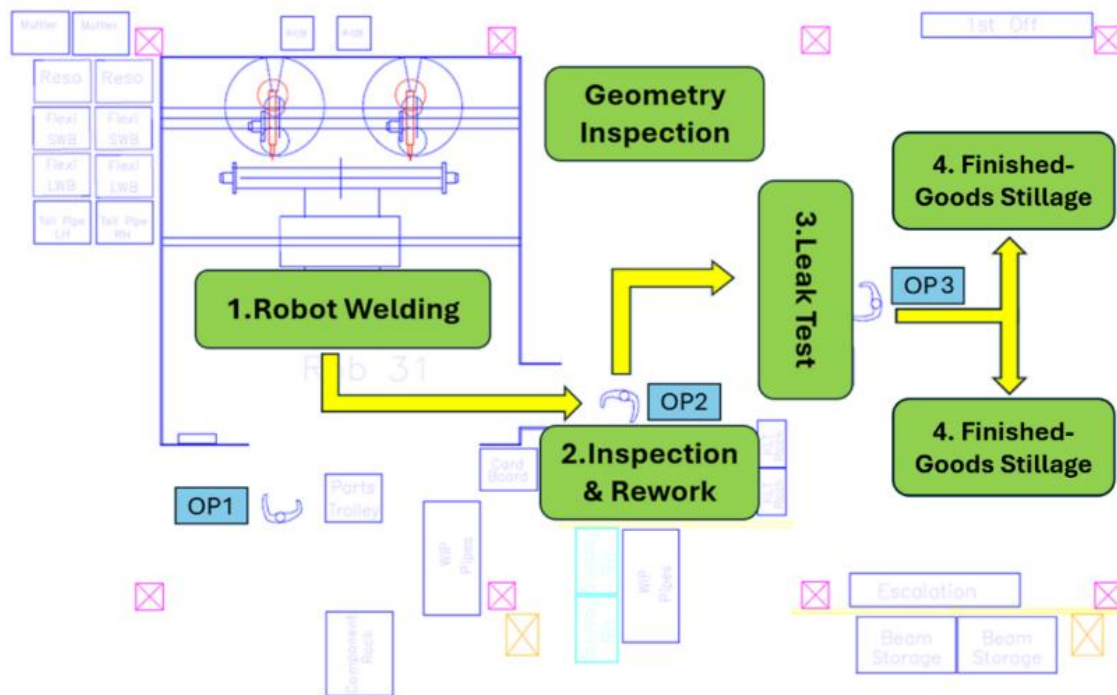


Figure 7: Robot 31 cell layout and process flow.

The transfer of exhaust assemblies between the leak tester and finished-goods stillage was initially designed as a two-person operation with lower throughput. In 2024, the operation transitioned to a single-operator model as part of a process-improvement initiative that consolidated work elements and removed one team member. However, no manual handling risk assessment was conducted at the time, leaving an elevated ergonomic risk undetected. Between February and August 2025, two incident reports were submitted for musculoskeletal disorder-related injuries involving operator No. 3. This risk is significant, as national statistics indicate that the average cost of a UK work-related ill-health case in 2022/23 was £21,500 (Health & Safety Executive, 2024a), as shown in Figure 8. Musculoskeletal disorders (MSDs) accounted for approximately 32% of these cases, resulting in an average of 14.3 working days lost per case (Health & Safety Executive, 2024b).

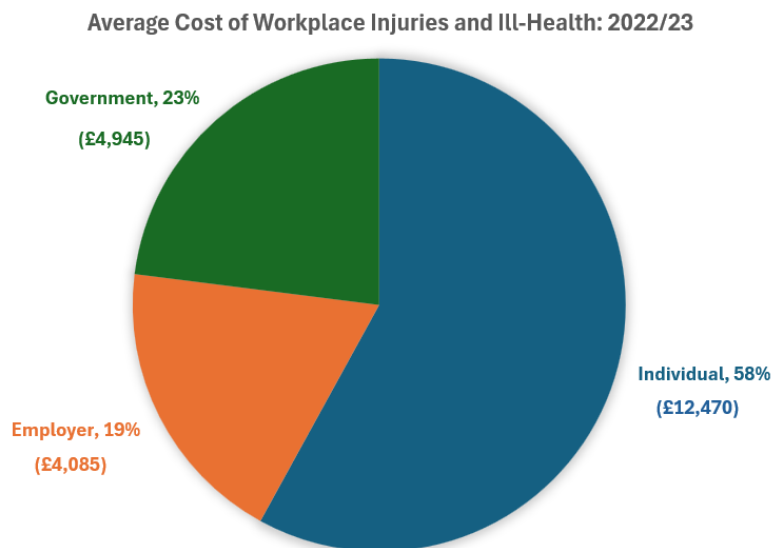


Figure 8: Chart of average workplace injury costs in 2022/23 (Health & Safety Executive, 2024a).

Following the incident reports, the project manager conducted a manual handling assessment in September 2025 using the Health and Safety Executive's (HSE) online MAC (Manual Handling Operations Assessment Charts) tool (Appendix 8.1 & 8.2). The tool aids in recognising high-risk factors, categorises risk levels using a colour coding system, and generates reports that recommend control measures to improve workplace safety (Health and Safety Executive, 2025). The process involved video-recording the operation (Figure 9) and analysing the footage offline. This allowed for a careful element-by-element assessment against the risks outlined in the MAC guidebook. Visual aids, such as the chart illustrating the vertical lift zones (Figure 10), were used to assist in referencing and interpreting the assessment criteria. The reports highlighted multiple amber risk factors - a medium risk that requires examination of tasks - and one red risk factor, indicating a high-level risk that requires prompt action.

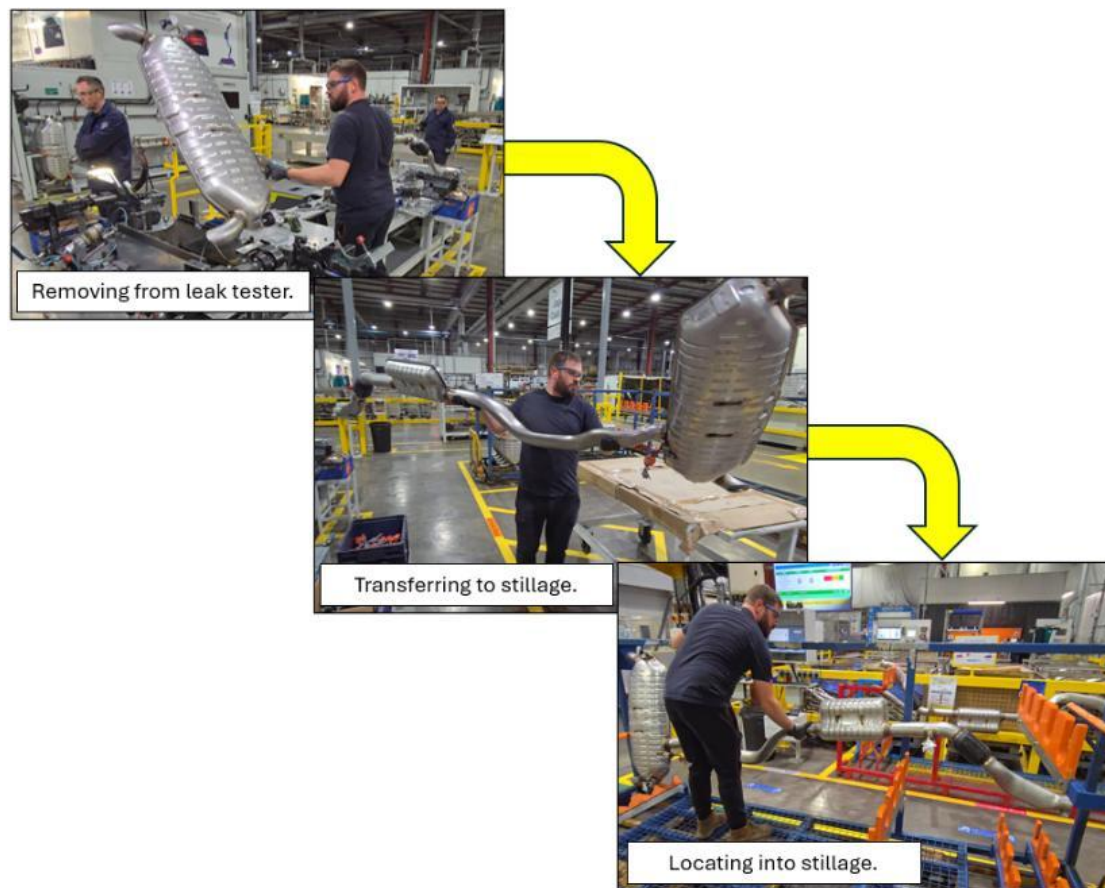


Figure 9: Manual exhaust system handling phases.

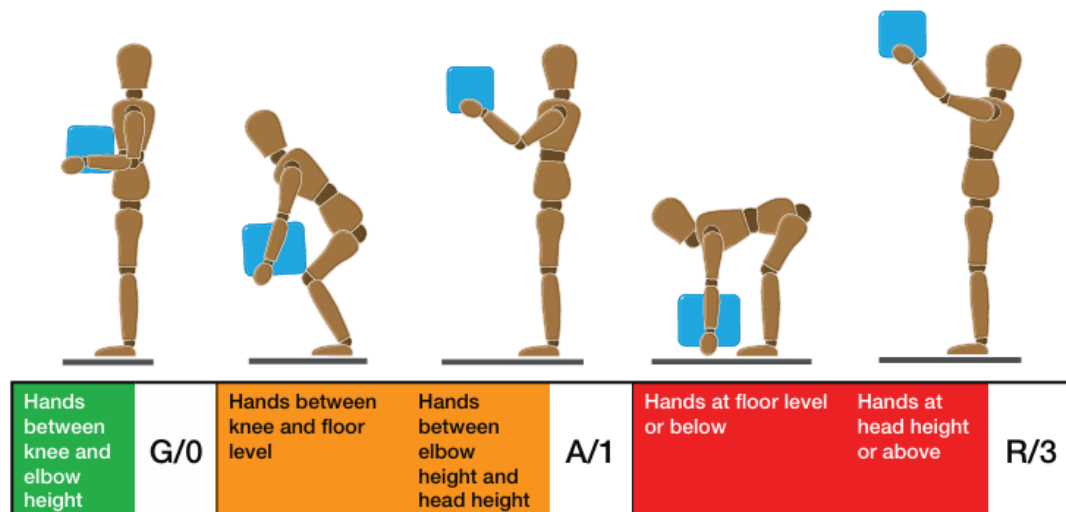


Figure 10: Vertical lift zones assessment guide (Health and Safety Executive, 2025).

Following the MAC assessments, Highpoint's Health and Safety Supervisor mandated that two team members must lift and carry the exhaust system between the leak test and packing operations. Although this action reduced the asymmetrical torso load to

an amber rating, several other risk factors remained in the amber category; additionally, the cycle time was also affected.

The project manager and process engineer conducted time-and-motion studies in October 2025 to quantify the change in cycle time resulting from the implementation of the two-person lifting requirement. The process was observed directly, with each operation element timed on 10 separate occasions to determine the average value. The initial study (Appendix 8.3), based on Operator 3 transferring the exhaust system between the leak tester and the finished-goods stillage, produced a cycle time of 212 s (equivalent to 17 parts per hour). The subsequent study (Appendix 8.4), conducted with Operators 2 and 3 performing the task jointly, recorded a cycle time of 227 s (15.9 parts per hour), representing an increase of 15 s. This increase in cycle time posed a challenge in maintaining the required production output to meet customer demand within the standard 108-hour production week. As shown in Table 1, utilisation rose to 105%, necessitating production during premium working hours.

Table 1: Robot 31 capacity utilisation with a 2-person lift

Part Description	Weekly Demand	Ideal Planned Cycle Time (sec)	Percentage Scrap	Total required weekly parts	OEE	Percentage Utilisation	Hours Required Per Week
L460 P6 SWB	400	227	1	404	90%	26.2	28.3
L460 P6 LWB	400	227	1	404	90%	26.2	28.3
L461 P6	800	227	1	808	90%	52.4	56.6
Totals	1600	-	-	1616	-	105	113

To prevent missed orders and potential loss of business, a six-hour Saturday shift was introduced to maintain customer delivery requirements, resulting in an additional annual cost of £84,677 (Table 2). The combination of ongoing operator safety concerns and extra costs prompted the operations manager to request an investigation into a suitable handling device for this operation.

Table 2: Premium working costs with a 2-person lift

Description	Value
Fully fringed labour rate per hour	£23
Saturday overtime rate (1.5x base rate)	£34.50
Daily plant operational cost	£1,200
No. of operators	3
Overtime hours required	6
Weekly premium working cost	£1,821
Annual premium working cost	£84,677

As part of this investigation, it was identified that Robot 31 had previously manufactured a larger and heavier product using a vacuum lift-assist system for handling between operations (Figure 11). However, differences in geometry and handling requirements meant the existing system was unsuitable for the current exhaust assembly. The H-style gantry framework, vacuum pump, lift tube, and control handle from this system remained in place, providing the foundation for a new lifting solution. Furthermore, vacuum lift-assist equipment is already utilised in several other manufacturing areas across the Highpoint site, reinforcing its proven effectiveness, operator familiarity, and maintenance support within the facility.

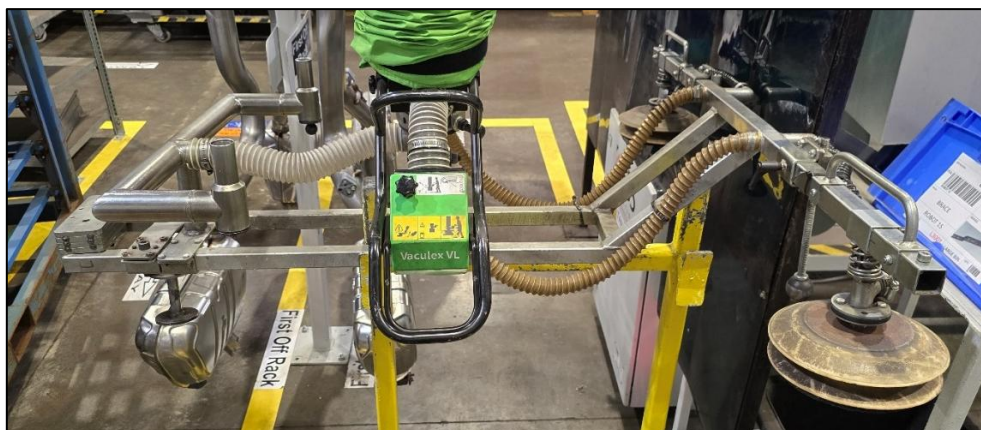


Figure 11: Old-level lift assist end-effector from Robot 31.

1.3. Aim and Objectives

1.3.1. Aim

This project aims to design, develop, and validate a custom end effector for a vacuum lift assist system that enables the safe and efficient handling of the P6 MHEV Cold End exhaust system at Tenneco Highpoint, ensuring compliance with ergonomic and safety standards while maintaining production efficiency.

1.3.2. Objectives

The project includes the following objectives:

1. Eliminate HSE red-category risks and reduce amber risks to green wherever practicable.
2. Integrate a new end effector with the existing gantry framework, pump, and controller system already available at Tenneco.
3. Ensure the mechanism can pivot the exhaust system from the horizontal to the vertical plane between operations.
4. The final solution shall be operable by a single team member and shall not reduce the cycle time below 212 s (17 PPH).
5. Select and justify appropriate materials and manufacturing processes to meet production lifetime volumes (Table 3).
6. Incorporate a robust maintenance and inspection regime into the design to maximise reliability.
7. Ensure manufacturing and implementation costs do not exceed £20,000; this figure was stipulated by the Operations Manager and relates to the cost of similar equipment purchased.
8. Validate the design using CAD (computer-aided design) and CAE (computer-aided engineering) tools, ergonomic assessments, and risk analyses.

Table 3: P6 MHEV lifetime volumes

Annual Volumes											
Engine	Platform	Programme	2026	2027	2028	2029	2030	2031	2032	2033	2034
P6 MHEV	MLA-H	L460	36,206	35,341	34,637	20,999	23,660	24,625	12,648	2,204	0
		L461	33,918	29,565	25,206	22,798	19,332	17,673	15,773	7,601	1,267
Sub Total			70,124	64,907	59,843	43,796	42,991	42,298	28,420	9,805	1,267
Grand Total			363,452								

1.4. Report Structure and Timing

Chapter 2 reviews research across several subject areas relevant to the project, including the mechanical design process, vacuum lifting systems, existing handling equipment, standards and compliance, and ergonomics.

Chapter 3 defines the product by identifying the customer groups and their requirements, which are then translated into engineering specifications and success criteria.

Chapter 4 presents the conceptual design stage, where multiple functional design solutions are generated using the production design specification developed in Chapter 3. These concepts are evaluated, and one of each of the functional design sub-systems is selected for further development. Investigations into suitable materials and manufacturing processes are also conducted, along with a preliminary risk assessment.

Chapter 5 details the design refinement phase, using CAD and CAE tools, including finite element analysis (FEA), to analyse and optimise the chosen concept. Once the final design is completed, manufacturing quotations are obtained.

Chapter 6 develops the business case and presents it to the senior management team for approval to manufacture the proposed end effector design.

Finally, Chapter 7 concludes the report and provides recommendations for future work.

The initial project timing plan is illustrated in Figure 12.

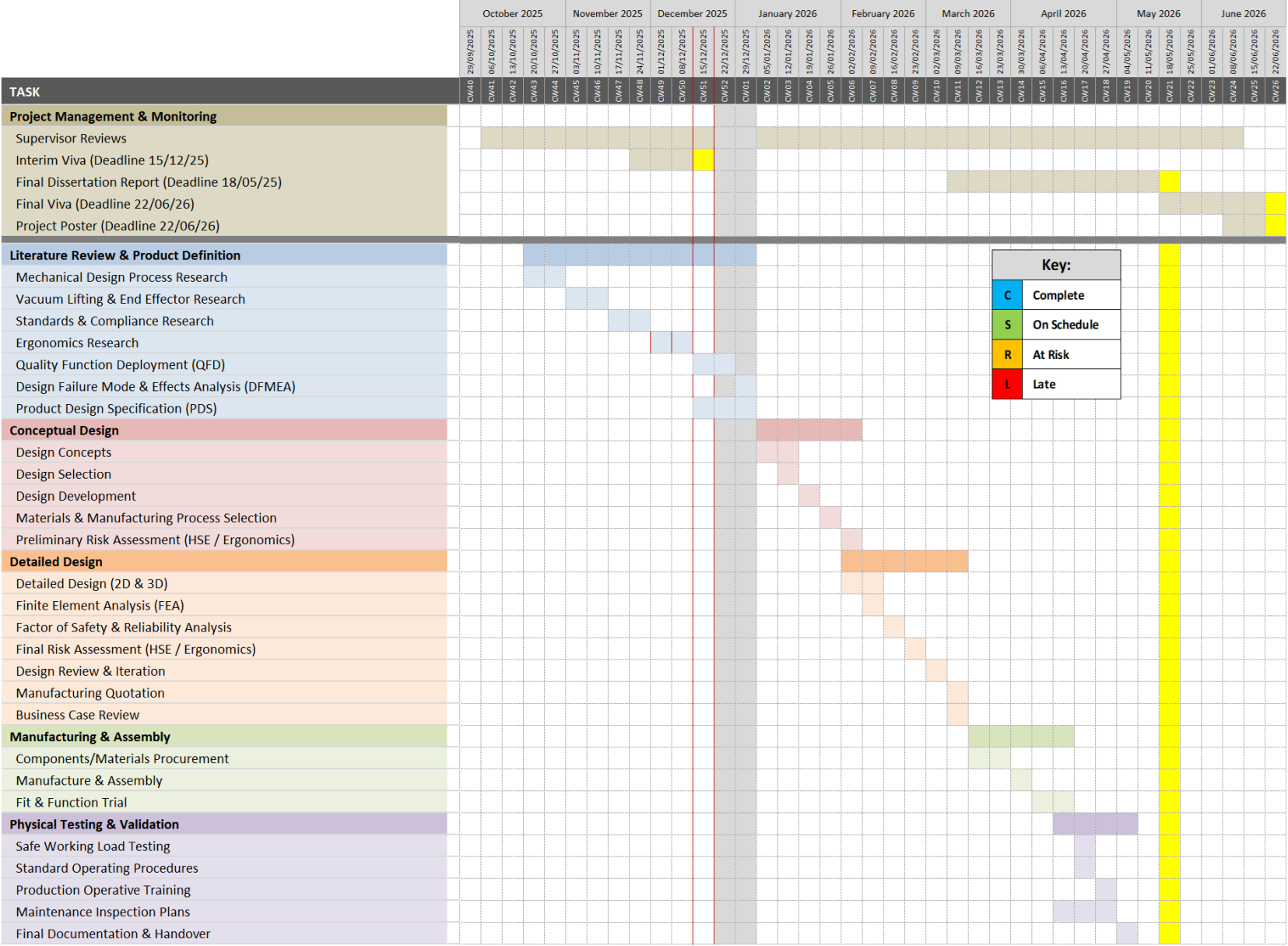


Figure 12: Initial project timing plan.

2. Literature Review

2.1. The Mechanical Design Process

2.1.1. Overview of the Mechanical Design Process

From an engineering perspective, the history of a product - from its initial development through to the end of its useful life - is described as the stages of a product's life. This should not be confused with the commercial term product life cycle, which represents the stages a product undergoes during its time on the market (The Welding Institute (TWI), 2025). In contrast, Ullman (2018) categorises a product's life into four discrete stages: design, production and delivery, use, and end of life. Each stage represents a distinct phase characterised by specific engineering decisions, resource requirements, and performance objectives. Understanding this progression is essential to the mechanical design process, as early design choices have significant downstream effects on manufacturing efficiency, product performance, and end-of-life sustainability. Figure 13 (Namouz *et al.*, 2010) illustrates the importance of investing sufficient time and resources during the early design phases of product development. As shown, the cost of implementing design changes increases significantly in the later stages, emphasising the value of identifying and resolving potential issues as early as possible.

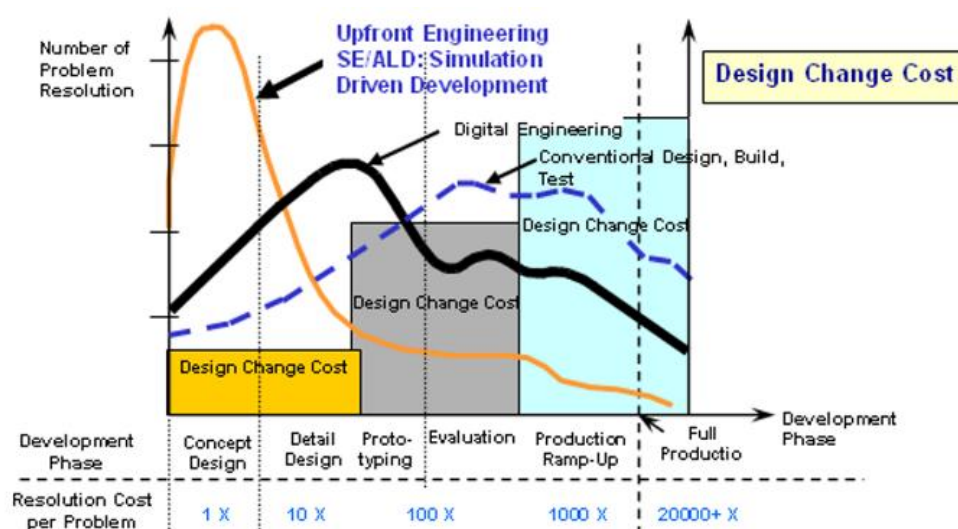


Figure 13: Engineering Change costs during various stages of product development (Namouz *et al.*, 2010)

In the context of this project, understanding these stages ensures that the vacuum lift-assist end effector is designed systematically, with particular emphasis on early-stage design evaluation to prevent costly modifications during the prototype or implementation phases. The following section, therefore, examines the mechanical design process in greater detail, outlining the structured methods that guide the development of engineered solutions.

2.1.2. Mechanical Design Frameworks for Bespoke Systems

The mechanical design process provides engineers with a systematic framework for translating a defined need into a functional, validated technical solution. While specific models vary in terminology and structure, the underlying principle remains consistent: design is an iterative decision-making process that balances performance, manufacturability, safety, and cost (Ulrich and Eppinger, 2012; Ullman, 2018; Nisbett and Budynas, 2024). Although such frameworks are often applied to the development of commercial products, where manufacturability and lifecycle economics are essential, their methods are equally relevant to bespoke or low-volume engineering systems. In these cases, the focus is on functional reliability, ergonomics, and integration within an existing manufacturing environment, rather than market success.

Across the literature, the process is typically divided into a series of progressive but overlapping stages. Nisbett and Budynas (2024) outline six key phases: identification of need, problem definition, synthesis, analysis and optimisation, evaluation, and presentation. Each stage refines the designer's understanding of the problem and the resulting solution, with iterative feedback loops between analysis and synthesis to improve accuracy and performance. In contrast, Ulrich and Eppinger (2012) frame the process around six product development phases - planning, concept development, system-level design, detailed design, testing and refinement, and production ramp-up - emphasising the transition from early concept exploration to production validation. Ullman (2018) similarly presents a five-stage model encompassing project definition, product definition, conceptual design, product development, and product support, highlighting formal review points between stages to ensure technical and organisational alignment.

Despite differences in terminology, these models share common characteristics. All begins with a clear definition of the problem and the establishment of measurable requirements, followed by iterative concept generation and evaluation, refinement through detailed design and analysis, and verification through testing or validation. Each author stresses that inadequate effort during the early design stages can lead to costly downstream changes, underscoring the value of early evaluation and communication within the design team (Ullman, 2018). This aligns with the engineering principle illustrated earlier in Figure 13, which shows that the cost of design modifications increases significantly as the project progresses to later stages.

When adapting these frameworks to a bespoke industrial design, such as the vacuum lift-assist end effector, the emphasis shifts from market-based validation to functional verification in the production environment. The process, therefore, focuses on ensuring ergonomic suitability, operational safety, and ease of integration with existing lifting equipment. Prototyping, finite-element analysis, and ergonomic assessment replace large-scale production testing as the primary validation methods. Table 3 summarises the key stages of the mechanical design process derived from these sources and how they apply to this project.

Table 4: Key project stages (Ulrich and Eppinger, 2012; Ullman, 2018; Nisbett and Budynas, 2024).

Stage	Key Activities	Application to the Project
Problem Definition	Define the problem to be resolved, including a clear definition of the desired outcome - the mission statement.	Defined through HSE MAC assessments and investigations into repercussions of injury claims.
Product Definition	Identify customers and their needs to create engineering specifications and success criteria.	Using the Quality Function Deployment framework to define specifications from operator feedback, HSE and company-specific requirements, existing equipment limitations, and research into previous design solutions.
Concept Generation	Develop multiple design ideas that satisfy the requirements. Propose manufacturing processes and materials.	Generation of multiple end-effector design concepts that interface with the existing vacuum-assisted lifting equipment and satisfy the requirements in the Production Design Specification.
Detailed Design, Analysis and Optimisation	Replace estimations with analytical computer-aided models; assess stress, reliability, ergonomics, and safety. Optimise design through multiple iteration loops.	Creation of detailed 3D models and 2D drawings. Ergonomic risk assessment via a 3D simulation. Finite Element Analysis for stress concentrations.
Presentation (Business Case)	Communicate the final design and justification for implementation.	Justification for why the financial investment outweighs the risks of injury claims.
Manufacturing and Assembly	Manufacture, assemble, and trial the chosen design solution.	Manufacturing and fitment of the new end effector. Fit and function tests.
Validation, Training & Handover	Conduct physical validation of the manufactured product. Provide training and sign-off equipment.	Validate the new end effector by conducting safe working load testing. Provide training and hand over the lifting solution to production.

Throughout this process, ergonomic and safety principles serve as critical design inputs, influencing geometry, handle position, and lifting orientation. By following a structured mechanical design process informed by these established frameworks, the project ensures a technically sound, operationally efficient solution.

2.1.3. Integration with Ergonomics and Safety

Ergonomics, also known as human factors engineering, is the science of designing tools, systems, and environments to align with human capabilities and limitations, thereby enhancing safety, comfort, and performance. The term was first coined in 1949 by a group of physiologists and psychologists in the United Kingdom who, in the same year, founded the Ergonomics Research Society (UC Berkeley, 2020). These researchers recognised that improving the interaction between people and equipment could increase productivity, reduce human error, and enhance health and safety (MisterRolls, 2012).

Throughout the mechanical design process, ergonomic principles serve as essential design inputs, influencing component geometry, control interfaces, and operator posture. Before defining the product, the fundamentals of ergonomics are examined, including anthropometry - the measurement of the human body - and biomechanics, the study of body structure, function, and motion; Figure 14 illustrates how the weight applied to the spine varies substantially depending on the lifting method applied. Applying these principles ensures that the design is not only compliant with safety standards but also promotes ease of use; otherwise, operators may revert to previous manual handling practices, reintroducing the risks the design seeks to eliminate.

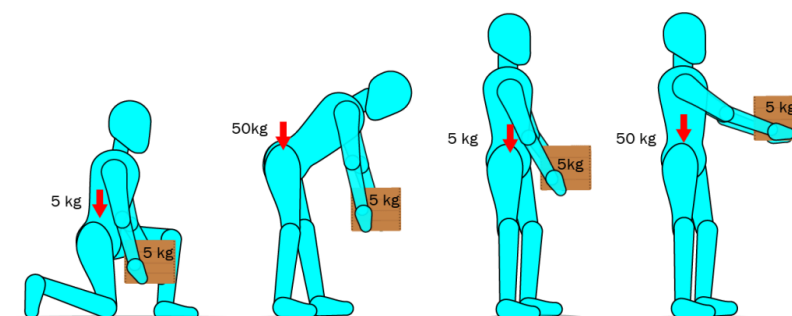


Figure 14: Impact of lifting techniques on body stress (Victor Hoe, 2022).

Applying ergonomic principles to the mechanical design process is critical to ensuring that the new lifting solution addresses the operator risks identified at Highpoint. The following section, therefore, reviews existing vacuum lifting equipment and end-effector configurations to inform the development of a safe and efficient system for this application.

2.2. Vacuum Lifting and End Effectors

Businesses worldwide employ a wide variety of mechanical lifting aids, including electrically powered systems such as chain hoists and cranes; material positioners such as scissor lift tables; pneumatically or hydraulically powered manipulators; and specialised tooling that uses friction-based grippers. Tenneco Highpoint chose to pursue a vacuum-based approach, leveraging existing experience with vacuum-assisted equipment on other production lines and the pre-installed vacuum-based gantry system on the cell, which had been utilised for a previous product. The following section, therefore, examines vacuum lifting technology in greater detail and its relevance to the development of the proposed end effector.

2.2.1. Overview of Vacuum Lifting Technology

The word vacuum has Latin origins, meaning 'empty'. This stems from the fact that an ideal vacuum contains no matter. However, such a state cannot be achieved. Space is often described as an extreme vacuum, yet even the deepest regions still contain around one atom per cubic meter (Coffey, 202AD). It wasn't until 1958 that the American Vacuum Society defined a vacuum as a space with gas pressure below atmospheric pressure (less than 1 Bar). On Earth, an artificial vacuum is typically produced by removing gas molecules from a sealed chamber using mechanical or diffusion pumps, thereby reducing the internal pressure. The lower the system's absolute pressure, the higher the degree of vacuum (Roth, 2014).

The level of a vacuum can be split into the following categories:

- **Rough (or low)** – Atmospheric pressure to 1 mbar. Vacuum lifting technology operates in this range.
- **Medium vacuum** – Pressures between 1 and 10^{-3} mbar. This range is used in the manufacture of light bulbs.
- **High vacuum** – Pressures between 10^{-3} and 10^{-8} mbar. Metals are smelted and refined in this range.
- **Ultra-high vacuum** – Pressures between 10^{-8} and 10^{-11} mbar. Many semiconductor manufacturing processes are completed in this range.

Vacuum pumps are used to create low-pressure environments using two fundamental methods: gas transfer, in which molecules are mechanically removed from the chamber, and capture, in which molecules are immobilised by freezing or chemical reaction. Since no single pump can cover the entire vacuum range, different pump types - such as positive-displacement, kinetic, cryogenic, or getter pumps - are selected or combined based on the required operating pressure. As vacuum levels increase, systems typically become more complex and require greater energy to achieve and maintain lower pressures (TAWI, 2020).

Vacuum lifting systems typically operate in the low-vacuum range, achieving pressures between -500 and -850 mbar, which is often expressed as a vacuum percentage (50% to 85%). The system interfaces with the object using suction cups, typically made of nitrile or silicone rubber, selected for their ability to form an effective seal. The reduced internal pressure then creates a pressure differential relative to atmospheric pressure, forcing the cup firmly against the surface (Figure 15). The greater the suction cup's surface area, the greater the load it can safely lift (IMI Norgren, 2019).

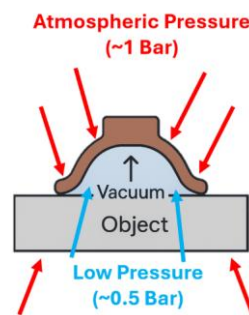


Figure 15: Vacuum cup sealing diagram.

Vacuum suction cups may be connected either to a separate hoist structure or to a tube-assisted lifting system. In tube-assisted systems, such as the one illustrated in Figure 16 (Anver Corporation, 2025), the vacuum tube itself is a compressible load-bearing structure and typically operates at 0–60% vacuum. According to TAWI (2020), the suction cup area should be approximately 250% of the lift tube's cross-sectional area, ensuring the system can safely support 2.5 times the intended lifting capacity.

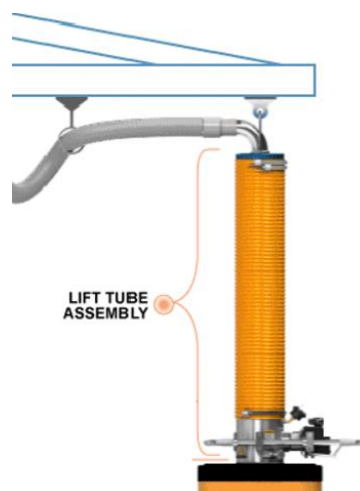


Figure 16: Vacuum lift tube assembly (Anver Corporation, 2025).

Vacuum pressure is monitored using either direct-reading or indirect-reading gauges. Direct-reading gauges measure the actual mechanical force exerted on an elastic element and are suitable only for the rough vacuum range, typically down to around 1 mbar. Lower pressures require indirect-reading gauges, where pressure is inferred from a gas property such as thermal conductivity or ionisation. In low-vacuum systems, such as the vacuum lifting systems discussed in the next section, simple mechanical gauges - such as compound Bourdon or diaphragm gauges - are commonly used due to the relatively high gas density (Figure 17). Capacitance diaphragm or piezoresistive gauges may be used in vacuum lifting control systems that require digital feedback for safety monitoring (Hata. David M., Brewer. Elena V. and Louwagie. Nancy J., 2023).

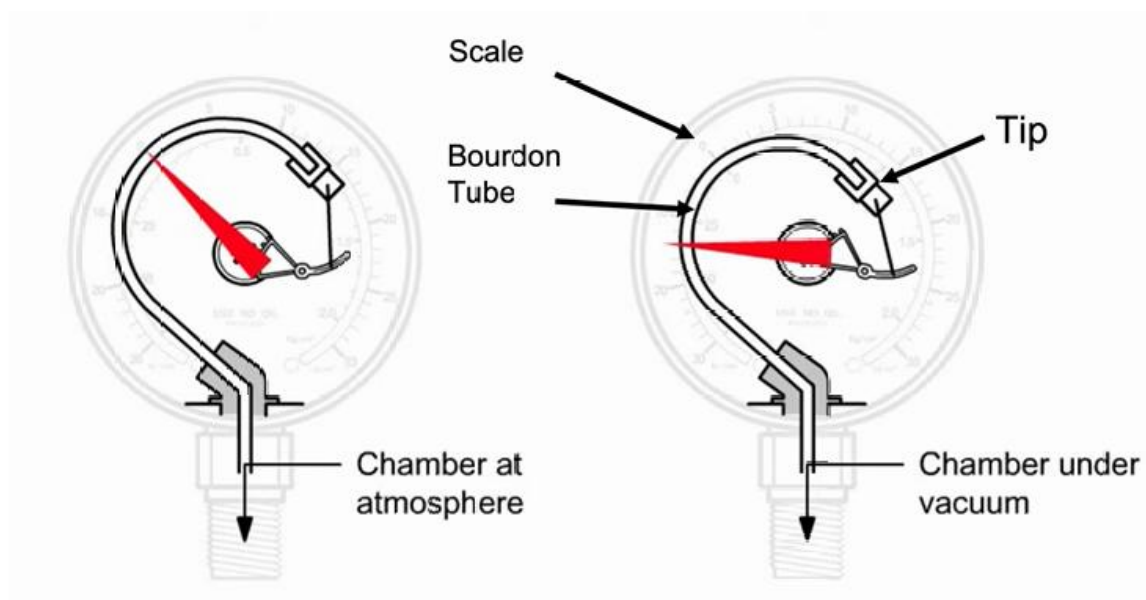


Figure 17: Bourdon gauge structure (Hata. David M., Brewer. Elena V. and Louwagie. Nancy J., 2023)

2.2.2. Analysis of Vacuum Lifting Case Studies

A review of five case studies demonstrates the consistent benefits of vacuum lifting technology in improving ergonomics, safety, and handling performance across diverse industrial settings. In logistics operations at Kuehne & Nagel, vacuum lifters enabled single-operator handling of 15-100 kg loads (Figure 18), reduced physical strain, and maintained productivity over long shifts (TAWI, 2025). Similarly, a packaging pick-and-

place system demonstrated that vacuum gripping can significantly reduce manual errors and improve cycle time when handling variable-shaped items, highlighting the importance of pressure control and adaptable suction configurations (Farooqi, Yusoff, and Chung, 2019).

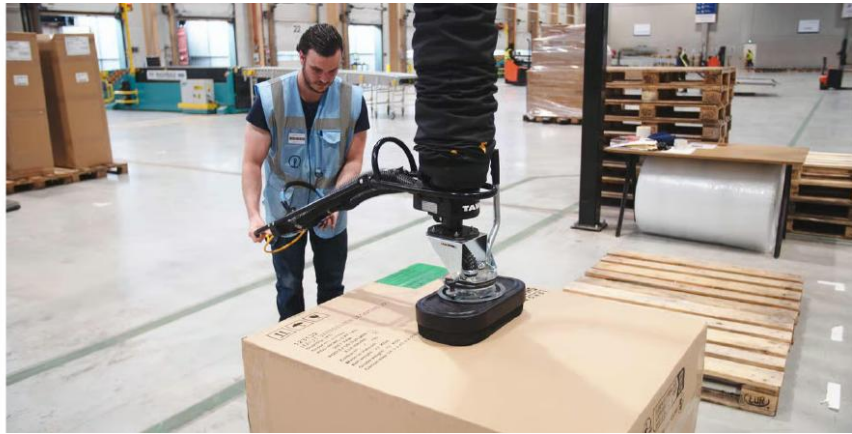


Figure 18: TAWI packaging vacuum lift assist system (TAWI, 2025).

Research involving dual-arm robot manipulation verified that vacuum systems can be effectively combined with mechanical support to manage asymmetric or challenging geometries, an insight applicable to the irregular form of automotive exhaust assemblies (Hayakawa *et al.*, 2023). Another study by The Vacuum Lifting Company demonstrated that safety can be significantly improved through pump redundancy, ensuring load security even in the event of a single pump failure - a fundamental requirement when handling loads of up to 50 tons, as illustrated in Figure 19 (Dynaflor, 2022). Collectively, these case studies reinforce the suitability of a vacuum-assisted solution at Tenneco Highpoint, supporting its ergonomic, safety, and operational objectives.



Figure 19: Steel plate vacuum lifting system (Dynaflor, 2022).

2.2.3. Analysis of Existing Handling Technologies for Exhaust Assemblies

To support the development of the lifting solution for the P6 MHEV exhaust system, five commercially available exhaust-handling devices were analysed to identify their design approaches, operational capabilities, and limitations (Appendix 8.5). The examples incorporated a range of clamping mechanisms and energy sources, with most utilising an H-Frame gantry arrangement that provides a high degree of movement flexibility. Evaluating these designs offers insight into key features that align with the project objectives, including safe, low-effort handling, the ability to pivot between horizontal and vertical planes, and compatibility with the existing vacuum-assist lift tube. The key characteristics of the five handling devices are summarised in Table 5. This assessment forms the basis for defining the requirements of the new end effector and selecting design features that are both practical and compatible with the vacuum lifting infrastructure already in place at Tenneco Highpoint.

Table 5: Comparative analysis of existing exhaust handling devices (Knight Global, 2012; Givens Engineering, 2023; Movomech, 2025; PowerBuilt, 2025).

Device	Energy Sources	Motion Capability	Gripping Method	System Complexity	Ease of Use	Potential Design Elements for P6 MHEV Exhaust
Movomech	- Compressed air	Offers extensive X–Y planar mobility, combined with 90° tilting capability and rotational freedom about the vertical axis.	Two double-acting pneumatic clamps interface with the exhaust pipe.	Moderate complexity; mixed pneumatic/mechanical system.	- Two sets of controls located 180° apart. - Requires minimal operator effort.	- Horizontal to vertical pivoting mechanism. - Pneumatic clamps.
Givens Engineering	- Vacuum energy	Offers extensive X–Y planar mobility and rotational freedom about the vertical axis. The system lacks a tilting mechanism.	Multiple vacuum suction cups.	Low complexity, except for the controls arrangement.	- Single set of controls, mounted 45° from the horizontal plane. - Controls are positioned lower than the exhaust assembly.	- Vacuum suction cups.
PowerBuilt	- Compressed air - Electricity	Overhead-mounted articulated arm with 300° rotation. The system lacks a tilting mechanism.	Five v-profile saddle locations with double-acting pneumatic clamps.	High complexity; requires electrical and pneumatic power sources.	- Single set of controls - Requires minimal operator effort. - Large footprint required to operate.	- V-profile saddle locations. - Pneumatic clamps.
Knight Global	- Compressed air	Offers extensive X–Y planar mobility, combined with 90° tilting capability and rotational freedom about the vertical axis.	Two pneumatic claw-style grippers.	- High mechanical complexity; multi-axis movement.	- Two sets of controls located 180° apart. - High control position, relative to the exhaust.	- Pneumatic claw-style gripper.
TAWI	- Vacuum energy	Offers extensive X–Y planar mobility and rotational freedom about the vertical axis. The system lacks a tilting mechanism.	Two vacuum suction cups with a mechanical support to maintain the centre of gravity.	Simple, low-cost design.	- Single set on controls that can be rotated 360°. - Ergonomic control height.	- Vacuum suction cups. - Adjustable controller position. - Mechanical support.

2.2.4. Vacuum Lifting Infrastructure and Operational Interfaces

Operational Interfaces

Cell dimensions define operational clearances and establish spatial constraints for the end effector's motion. Figure 20 presents a CAD illustration of the equipment associated with this project. Key dimensions - such as the distance between equipment, the lift tube stroke, and equipment heights - are detailed in Appendix 8.6. This information helps ensure the end effector design operates safely within the intended user environment.

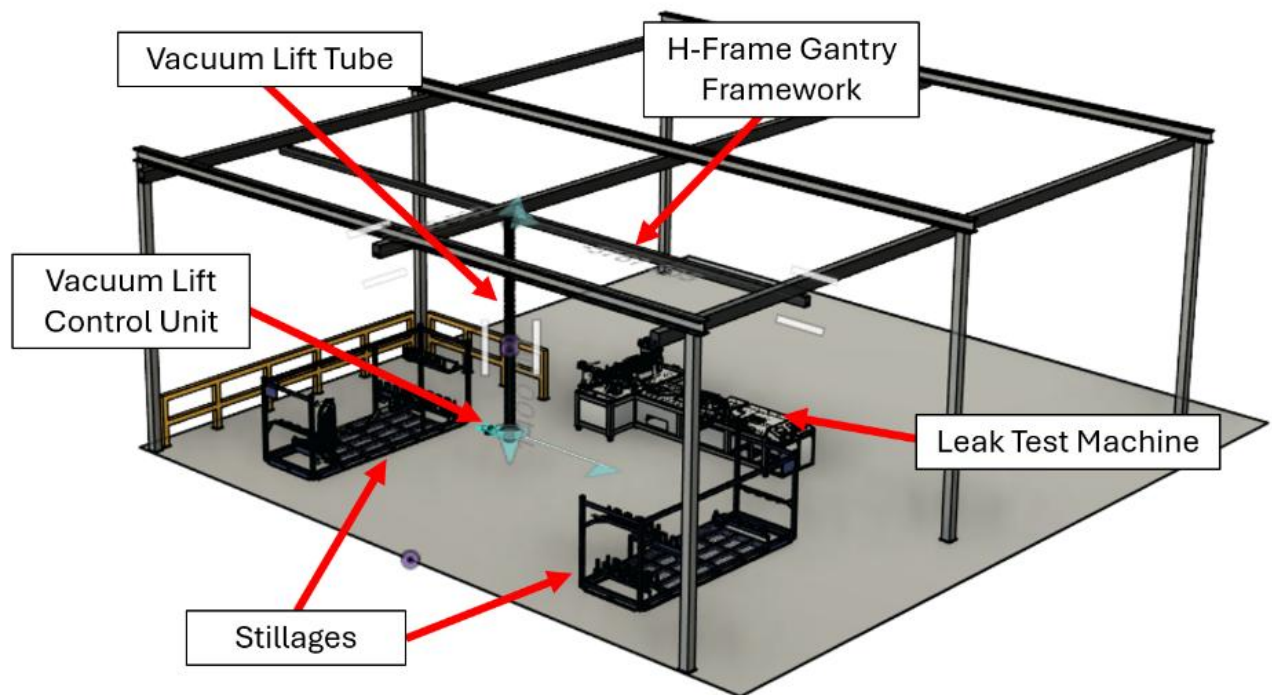


Figure 20: 3D CAD illustration of Robot 31 cell layout.

Several regions of the exhaust assembly cannot be interfaced by the end effector due to equipment and part constraints. Appendix 8.7 illustrates the interface limitations imposed by the stillage and leak tester, resulting from fixturing regions or clamping mechanisms. Modifying the stillages to mount the exhaust assemblies horizontally was not considered feasible, as the stillages are customer-owned assets. The inlet pipe is classified as a part constraint because it is connected to a flexible coupling; fixturing on this pipe could place undue strain on the coupling. A complete depiction of prohibited exhaust contact areas is provided in Figure 21.

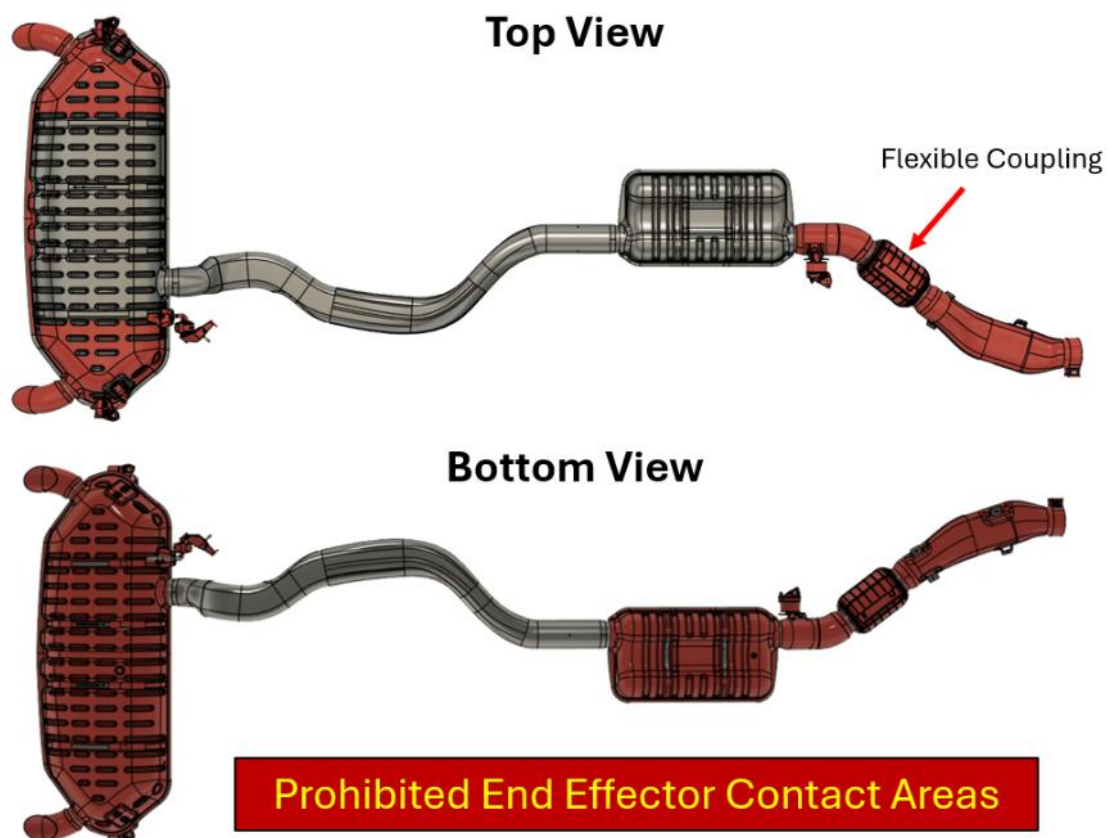


Figure 21: Regions of the exhaust assembly where end effector contact is not permitted.

Vacuum Lifting Infrastructure

The existing vacuum lifting infrastructure on Robot 31 consists of an H-frame gantry system, providing the Ø180 mm lift tube with an X-Y planar operating range of 135 m². The lift tube also offers a Z-axis stroke of 1.8 m. At the end of the lift tube is a TAWI VM60 controller, weighing 12.2 kg and rated for loads up to 80 kg. The system is powered by a Becker SV400/2 side-channel vacuum pump (Appendix 8.8). However, the current configuration lacks a vacuum gauge, which is critical for real-time safety monitoring and verifying adequate suction. Without pressure monitoring, insufficient vacuum could cause the product to dislodge from the lift assist, potentially injuring the operator.

Side-channel blowers use a rotating impeller to draw air through the suction inlet and accelerate it outward into a side channel, where centrifugal forces cause the air to move helically through the blower. Each pass through the channel increases compression, generating vacuum or pressure through multi-stage internal compression. Figure 22 illustrates the operating principle of a typical side-channel blower. As intake pressure decreases (i.e., becomes more negative in relative terms or lower in absolute terms), the suction air rate also falls, as shown in Figure 23 (Becker, 2025).

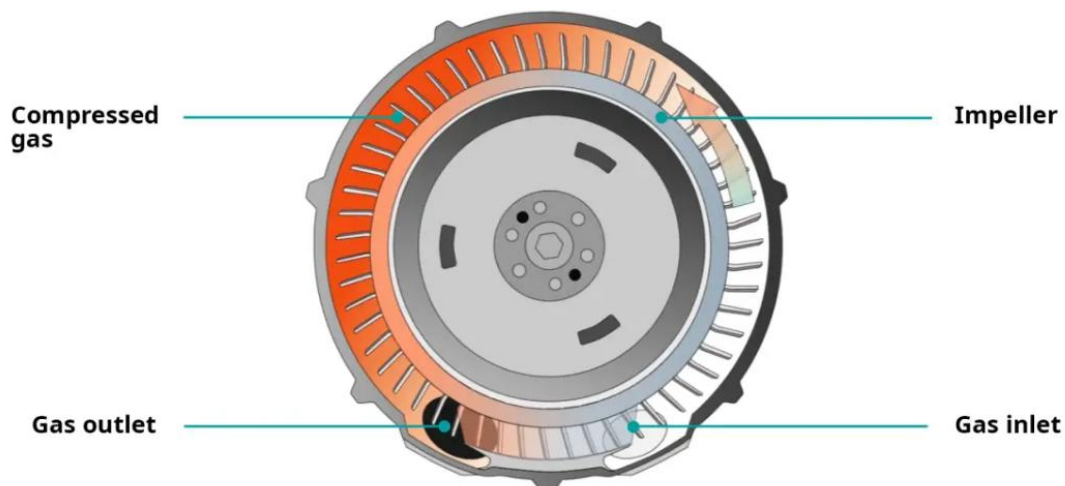


Figure 22: Operating principle of a side-channel blower (Busch Vacuum Solutions, 2020).

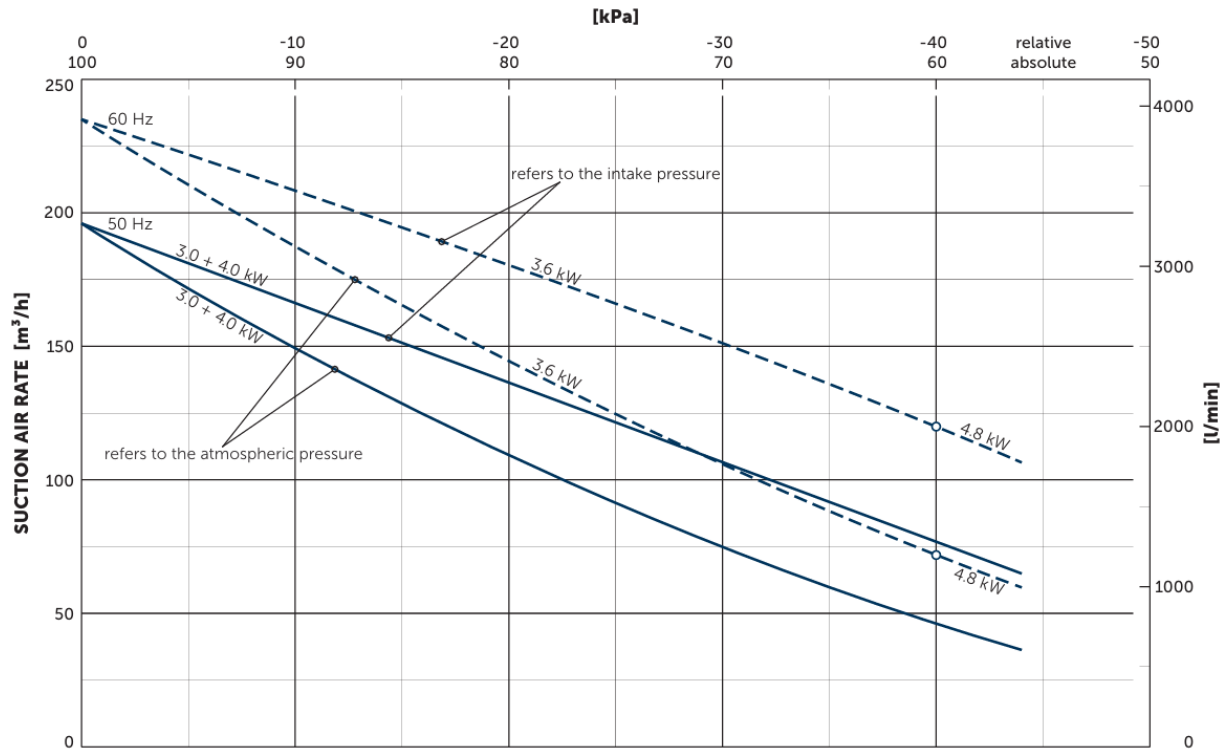


Figure 23: Becker SV400/2 pump performance curve (Becker, 2025).

This pump achieves a maximum vacuum of approximately -44 kPa (relative), equivalent to roughly 40% vacuum. According to the ideal gas law, pressure is directly proportional to absolute temperature at constant volume; over the factory's temperature range of 15-25 °C (288-298 K), this results in a pressure variation of only around 3.5%, which is negligible for the performance of a rough-vacuum lifting system (Umrath, 2016).

Maximum End Effector Weight Calculation

The first phase involves calculating the force exerted by the lift tube using the following equation:

$$F = \Delta P \times A$$

Step 1 – Converting the tube diameter to area:

Diameter $d = 0.18 \text{ m}$

$$A = \frac{\pi d^2}{4}$$

$$A = \frac{\pi(0.18)^2}{4}$$

$$A = \frac{\pi(0.0324)}{4} = 0.02545 \text{ m}^2$$

Step 2 – Apply pressure differential:

Maximum vacuum = -44 kPa (relative to atmospheric pressure of 101 kPa)

So $\Delta P = 44,000 \text{ Pa}$

$$F = 44,000 \text{ Pa} \times 0.02545 \text{ m}^2$$

$$F = 1119.8 \text{ N}$$

Step 3 – Convert to kg

Gravity (acceleration) = 9.81 m/s^2

$$F = m \times A$$

$$\therefore \text{Load capacity (m)} = \frac{F}{A}$$

$$\therefore \text{Load capacity (m)} = \frac{1119.8}{9.81} = 114.1 \text{ kg}$$

The maximum theoretical load the lift tube can support is 114 kg; applying a safety factor of 2 reduces this to 57 kg, which is below the VM60 controller's 80 kg safe working load. Considering the weight of the heaviest exhaust (27 kg) and the controller (12 kg), the end effector must be no greater than 18 kg.

Minimum Suction Cup Area Calculation

TAWI (2020) recommends ensuring the suction cup area is at least 2.5x the area of the lift tube, as discussed in Section 2.2.1.

$$\text{Minimum suction cup area } (A) = 2.5 \times 0.02545$$

$$\text{Minimum suction cup area } (A) = 0.0631 \text{ m}^2 (631 \text{ cm}^2)$$

The minimum suction cup area required is 631 cm².

2.3. Standards and Compliance

Standards and regulatory frameworks play a critical role in the design and operation of vacuum-based lifting systems. They ensure that equipment is engineered, installed, and used in a manner that minimises risk to operators while maintaining consistent safety and performance standards. For this project, compliance is essential not only to meet legal obligations but also to establish a robust engineering foundation that supports reliability, reduces operational hazards, and aligns with industry best practices. The following subsections summarise the key legislation, guidance documents, and organisational procedures that govern the use of lifting equipment in the UK and within Tenneco's internal safety framework.

2.3.1. HSE Guidance for Vacuum Lifting Systems

The HSE's Vacuum Lifting Equipment Guidance provides best-practice advice specific to vacuum lifting tubes. Relevant points include the need for sufficient gripping force, typically achieved by maintaining a pressure differential of around 550 mbar and a pad-to-tube area ratio that provides an inherent safety margin. The lifting tube, being a safety-critical component, must be designed to withstand fatigue, torsion, ageing, and environmental conditions. The guidance highlights potential failure modes, including vacuum loss, pump malfunction, and damage to the fabric tube. Regular inspection of seals, tube condition, and safety-critical components is strongly

recommended. Only content relating to vacuum lifting tubes applies to this project; guidance on detachable lifting attachments is not relevant (Health & Safety Executive, 2025).

2.3.2. Provision and Use of Work Equipment Regulations 1998 (PUWER)

PUWER places general duties on employers to ensure that work equipment is suitable, maintained, inspected, and used safely. For this project, PUWER requires that the vacuum lifting tube is appropriate for the task, maintained in an efficient condition, and inspected at intervals that reflect the risk of deterioration. Operators must receive adequate training and clear instructions, and the system must incorporate safe controls, isolation points, and appropriate warning indicators. PUWER also mandates clear equipment markings and the implementation of safe systems of work (Health and Safety Executive, 2014).

2.3.3. Lifting Operations and Lifting Equipment Regulations 1998 (LOLER)

LOLER applies specifically to equipment used for lifting loads and therefore directly covers vacuum lifting tubes. Key requirements include ensuring that the device has adequate strength and stability, that Safe Working Loads (SWLs) are clearly marked, and that lifting operations are properly planned, supervised, and carried out by competent personnel. LOLER also requires thorough examination by a competent person at defined intervals - typically every 12 months for lifting machines - and mandates defect reporting and record keeping. These obligations influence design decisions, load ratings, and ongoing maintenance planning (Health & Safety Executive, 2014).

2.3.4. Manual Handling Operations Regulations 1992 (MHOR)

MHOR requires employers to avoid hazardous manual handling where reasonably practicable and to minimise the risks associated with unavoidable handling tasks. The introduction of a vacuum lifting tube directly supports compliance by reducing operator effort and lowering the physical demands of handling operations. The proposed system is therefore intended to satisfy the core requirements of MHOR by mitigating manual lifting loads identified in the preliminary MAC assessment, which highlighted the need for a mechanical handling solution. However, achieving full compliance also depends on the device's ergonomic suitability, including the position and accessibility of the operational controls, and the force required to manoeuvre the lifting tube during normal use. These aspects will be evaluated further through task-specific risk assessments during the design analysis phase, ensuring that the solution reduces handling risks without introducing new ergonomic concerns (Health and Safety Executive, 2016).

2.3.5. Tenneco Health and Safety Procedure (EHS-PRO 803.00)

Tenneco's Cranes, Hoists, Slings and Lifting Devices Procedure establishes mandatory safety requirements for all lifting operations at its facilities, requiring strict compliance as a Cardinal Rule to prevent serious injury. This procedure applies universally to all employees, contractors, and visitors. Each site must adhere to both Tenneco standards and applicable local regulations, designate a Crane & Hoist Competent Person, and maintain a current inventory of all lifting devices. The procedure outlines specific responsibilities for management, supervisors, operators, and EHS personnel, including ensuring appropriate training, selecting appropriate equipment, and adhering to inspection and maintenance schedules.

All lifting equipment must be uniquely identified, clearly marked with its rated capacity, and subjected to rigorous checks, including daily pre-use inspections, periodic comprehensive inspections, and load testing before first use or after modification. Critically, defective equipment must be removed from service immediately. For this

specific project, the procedure strongly reinforces the requirement for all vacuum lifting equipment to be rated appropriately, inspected and documented, and further mandates that it be operated only by trained personnel (Tenneco, 2024).

Table 6 summarises the key requirements from the referenced standards and guidance documents applicable to this project.

Table 6: Compliance Requirements for the Proposed Vacuum Lifting System (Health & Safety Executive, 2014, 2025; Health and Safety Executive, 2014, 2016; Tenneco, 2024).

Standard / Guidance	Key Requirements Relevant to the Project
HSE Vacuum Lifting Equipment Guidance	• Identify hazards such as falling loads and loss of vacuum. • Ensure loads are suitable for vacuum lifting; avoid porous/flexible materials unless designed for. • Do not exceed Safe Working Load (SWL). • Provide clear vacuum gauges and warning indicators to enable early detection of vacuum loss. • Require daily and weekly inspections plus periodic examination by a competent person. • Operators must be trained, competent, and follow safe systems of work. • Risk assessment required to determine suitability of VLT for the task.
Provision and Use of Work Equipment Regulations 1998 (PUWER)	• Equipment must be suitable for its intended use and environment (Reg. 4). • Must be maintained in efficient working order (Reg. 5) and inspected where necessary (Reg. 6). • Operators must receive adequate information, instruction, and training (Reg. 9). • Controls, emergency stops and stability requirements apply where relevant. • Requires risk assessments via the Management Regulations.
Lifting Operations and Lifting Equipment Regulations 1998 (LOLER)	• Applies because a VLT is classed as lifting equipment. • Loads must be secure. • Lifting equipment must be thoroughly examined at prescribed intervals (typically every 12 months unless acting as a lifting accessory, then every 6 months). • SWL must be clearly marked and not exceeded. • Particular attention needed for preventing load displacement.
Manual Handling Operations Regulations 1992 (MHOR)	• Duty to avoid hazardous manual handling where reasonably practicable. • Vacuum lifter provides <i>mechanical assistance</i> to reduce injury risk. • Must assess hazardous manual handling tasks using tools such as MAC (already completed). • Risk assessments must consider operator posture, environmental constraints, and force required to operate controls. • Maintenance of lifting aids required under MHOR + PUWER/LOLER where applicable.
Tenneco Lifting Equipment Procedure (EHS-P 803.00)	• Establishes mandatory internal safety rules for lifting equipment. • Requires equipment inventories, unique identification, and defined duty cycles. • Daily pre-use checks and periodic inspections are compulsory. • Initial 125% load testing required for new or modified equipment. • Operators must be trained and authorised. • Faulty equipment must be removed from service immediately. • Lifting devices must be used within marked SWL and safe operating procedures.

2.4. Ergonomic Considerations

2.4.1. Scope and Relevance to the Handling Device

Ergonomics integrates physical, cognitive, and organisational principles to optimise human well-being and system performance in production environments. For bespoke industrial tools such as the proposed vacuum lifting device, this requires designing interfaces, postures, and task flows that keep operators within safe biomechanical limits while maintaining takt time and product quality. Consistent with established guidance in production ergonomics, this section synthesises anthropometry, biomechanical loading, high-risk body regions, and recognised evaluation methods and translates these into design and validation requirements for use at Highpoint.

2.4.2. Anthropometry: Designing for the Worker Population

The design of the lift-assist controller should accommodate the intended user population, typically the 5th-percentile female to the 95th-percentile male, as recommended in Production Ergonomics (Berlin and Adams, 2017). Clearance-critical dimensions should be based on the 95th percentile, while reach and strength requirements follow 5th-percentile values. Where this range cannot be met with a fixed configuration, adjustability is required, consistent with principles in both Production Ergonomics (Berlin and Adams, 2017) and the Metric Handbook (Buxton, 2022). Handles must support a power grip and maintain the wrist in a neutral posture, avoiding excessive flexion, extension, or deviation.

Controls should be positioned within the primary reach envelope to keep the upper arm close to the torso. Maintaining low shoulder elevation is essential. Fewster and Dickerson (2021) show that the subacromial space reduces markedly between 60° and 90°, increasing the risk of tendon impingement. Frequent tasks should therefore occur at or below 60° of arm elevation, and work above shoulder level (>90°) should be avoided, as illustrated in Figure 24 (Jackson *et al.*, 2015). Using elbow-height data from anthropometric tables (Appendix 8.9) in the Metric Handbook (2022), the controller should fall within approximately 965–1220 mm, with limited upward

adjustment that remains below the 60° elevation threshold. This ensures neutral upper-limb posture and reduces shoulder loading during operation; Figure 25 (Ergonomic Partners, 2025) illustrates the neutral upper-limb posture range and an example of its implementation within a vacuum lifting device.

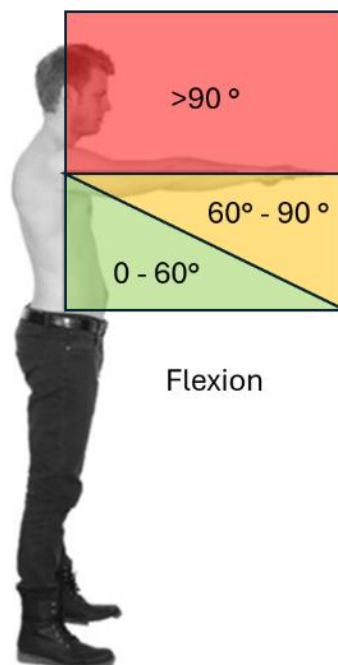


Figure 24: Shoulder flexion ranges and associated ergonomic risk zones (Jackson et al., 2015)

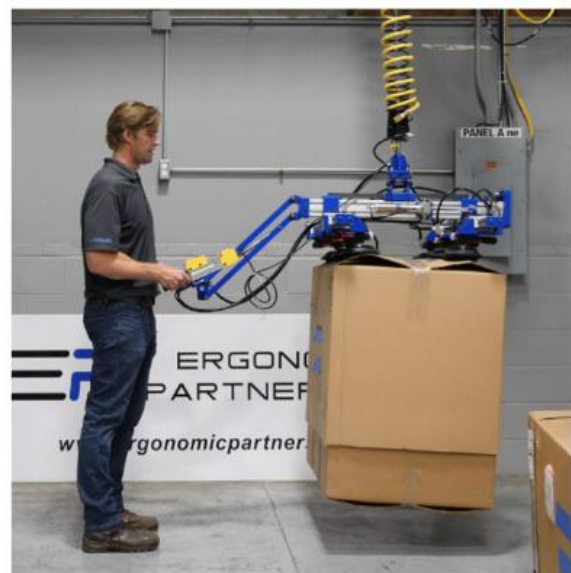
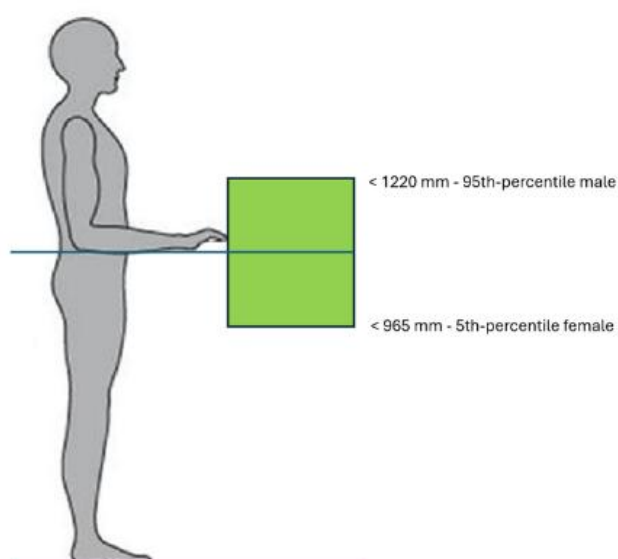


Figure 25: Anthropometrically derived handle height range for lift-assist operation (Ergonomic Partners, 2025)

2.4.3. Biomechanics and Physical Loading (Posture × Force × Time)

Musculoskeletal Disorder (MSD) risk arises from the interaction of posture, external forces, and time-related factors such as repetition and recovery (Berlin and Adams, 2017). Although the lift supports the product mass, residual operator forces remain during guiding, alignment, and actuation. Task design should therefore minimise trunk flexion and twisting, maintain arm postures below shoulder height, and limit wrist deviation.

Trunk flexion and rotation significantly increase spinal disc compression, particularly when combined with external loading, while sustained non-neutral postures further elevate cumulative biomechanical loading. Consequently, the device should avoid requiring sustained trunk flexion beyond near-neutral ranges or combined flexion - twist during capture and release. The trunk flexion and torsion limits defined in ISO 11226:2000, illustrated in Figure 26 (International Standards Organisation, 2024) are adopted as formal design constraints for the end effector. Designs that maintain neutral or near-neutral postures throughout the task cycle are associated with reduced fatigue, lower cumulative loading, and a decreased risk of musculoskeletal injury (Berlin and Adams, 2017; O. Odebiyi and Arinze Chris Okafor, 2023).

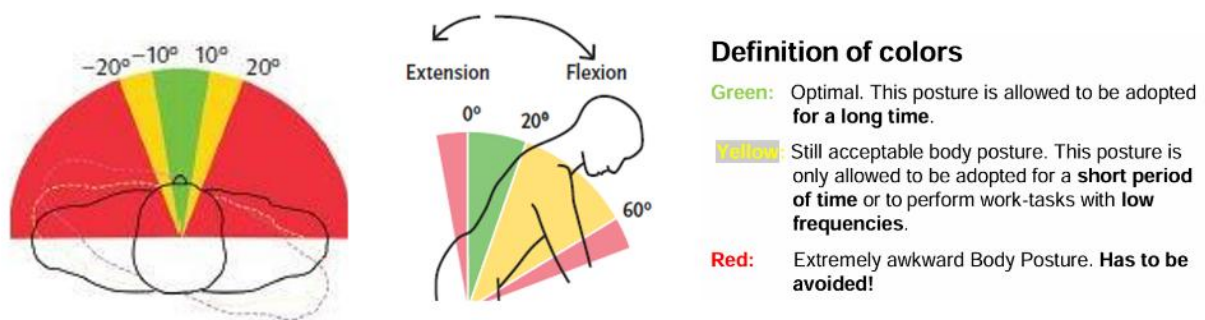


Figure 26: Trunk flexion and torsion posture zones defined by ISO 11226 (International Standards Organisation, 2024)

3. Product Definition

3.1. Introduction

As discussed in Section 2.1.1, the product definition phase of the mechanical design process is pivotal in developing a solution that satisfies customer requirements. During this stage, the Quality Function Deployment (QFD) methodology was applied to systematically translate customer needs - including regulatory, safety, and compliance requirements - into measurable engineering specifications. A Design Failure Mode and Effects Analysis (DFMEA) was also undertaken to identify potential design failures, evaluate their associated risks, and define preventative actions prior to the manufacturing phase. These outputs were then consolidated into a Product Design Specification (PDS), which provides a structured foundation for the subsequent conceptual design phase.

3.2. Quality Function Deployment

Quality Function Deployment (QFD) is a structured methodology for establishing clear relationships between customer requirements and engineering characteristics. Originating at Mitsubishi's Kobe shipyard site in 1972 (Hauser and Clausing, 1988), QFD has been shown to improve product quality, enhance customer satisfaction, and reduce development time by clarifying requirements early.

In February 2026, an investigation was conducted by the project manager using the eight-step QFD process summarised below:

1. Identification of stakeholders (customers).
2. Collection of customer requirements.
3. Prioritisation of customer needs.
4. Benchmarking against existing solutions.
5. Definition of engineering characteristics.
6. Establishment of relationships between customer requirements and engineering characteristics.
7. Setting measurable engineering targets.

8. Evaluation of interrelationships between engineering characteristics (technical correlation matrix).

(Ullman, 2018)

The outcomes of this process form the basis of the House of Quality presented in Figure 27.

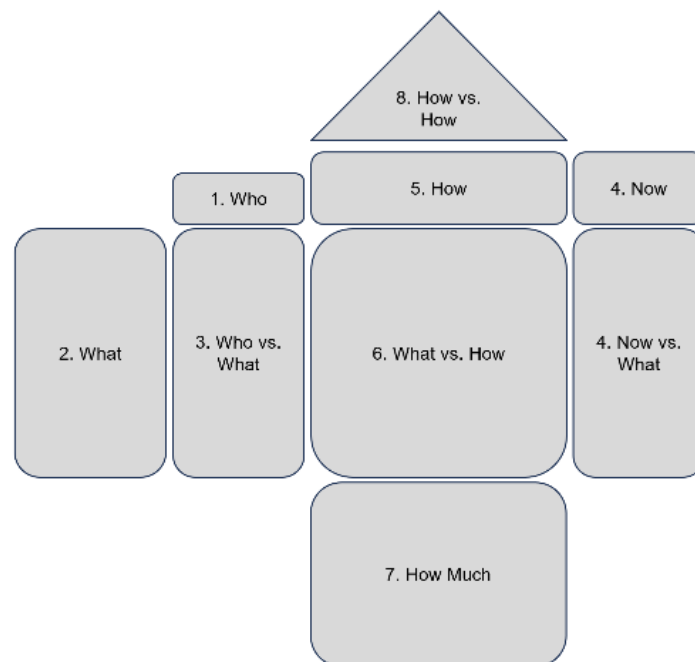


Figure 27: House of Quality (QFD Matrix).

3.2.1. Step 1: Customer Identification

A product's design influences multiple stakeholders throughout its lifecycle. Within the QFD framework, these stakeholders are typically categorised as external customers - those who directly interact with the product during operation or maintenance - and internal customers, who influence or are affected by the product's design, manufacture, and compliance.

For this project, five key customer groups were identified:

External Lift Assist Customers:

- Maintenance Technicians
- Production Operators (End Users)

Internal List Assist Customers:

- Standards and Regulatory Bodies
- Health & Safety / HSE
- Engineering / Manufacturing

These stakeholder groups form the basis for requirement elicitation in subsequent QFD stages.

3.2.2. Step 2: Determining Customers' Requirements

Following the identification of customer groups, requirements for each stakeholder category were established, many of which were initially identified in Sections 1 and 2. To further strengthen the design specification, a structured operator survey was distributed to six production personnel working on cells equipped with vacuum lifting systems (Appendix 8.10). The survey captured both quantitative (Likert-scale) and qualitative (open-ended) feedback regarding the current handling method and expectations for the proposed lift-assist system; a summary of the results is presented in Table 7.

Table 7: Operator survey results.

Requirement	Avg. Importance (1–5)
Safe and stable holding	5
Reduce manual effort	4.8
Smooth X–Y movement	4.6
Easy rotation	4.2
Comfortable control height	4

Open responses consistently highlighted lower back strain and awkward postures during alignment of the exhaust with equipment, reinforcing the need for ergonomic height adjustment and improved rotational control.

The Kano model is commonly applied at this stage to evaluate how product features influence customer satisfaction relative to functional performance. It classifies requirements into three categories: basic features, which are expected as standard

and only generate dissatisfaction when absent; performance features, where improvements lead to proportional increases in customer satisfaction; and excitement features, which are not anticipated by the customer but create delight when present, while their absence does not result in dissatisfaction (Noriaki, 1984). Figure 28 displays a Kano model that is populated with this project's customer requirements.

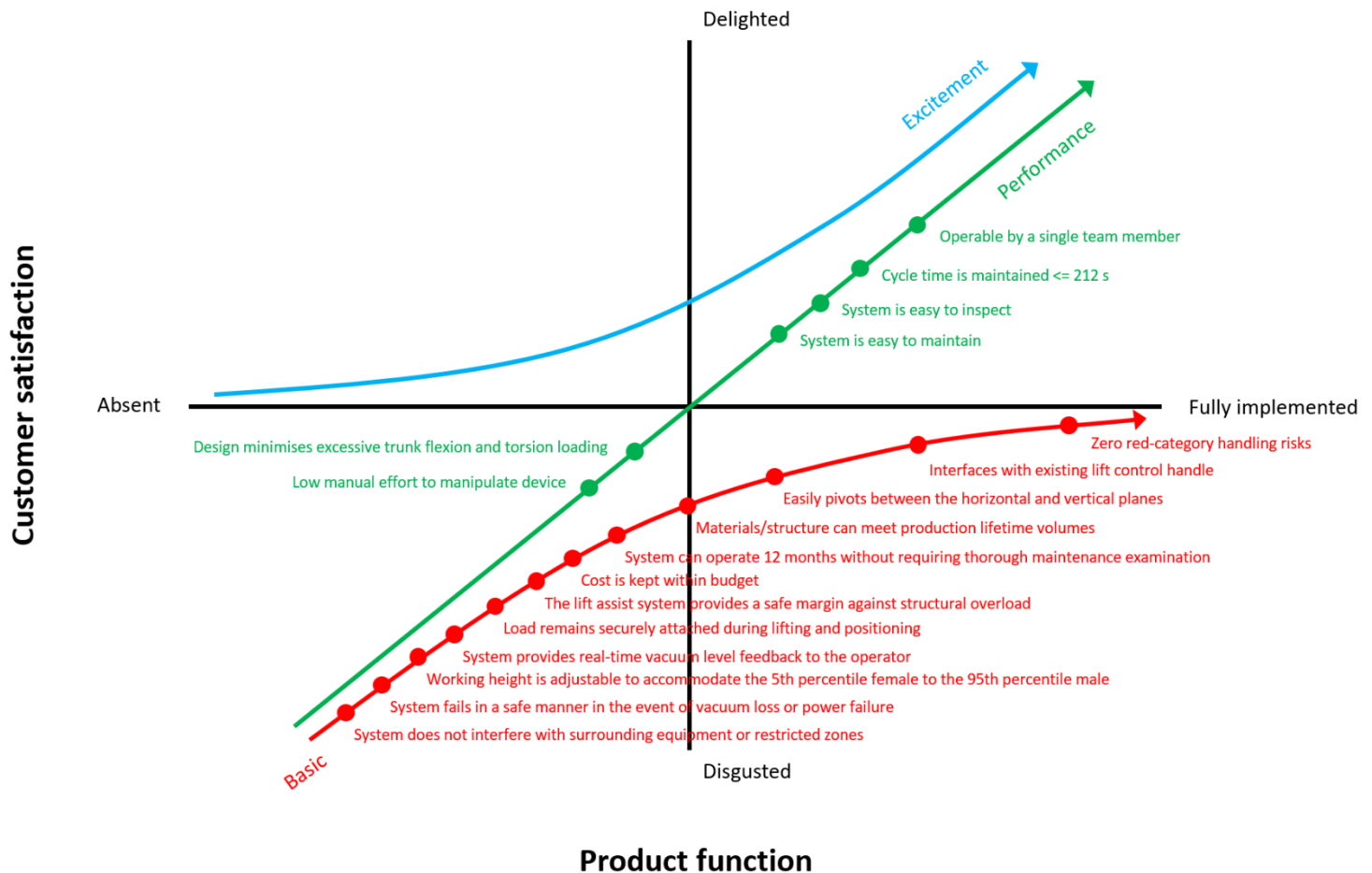


Figure 28: Kano model of end-effector customer requirements.

Certain statutory and regulatory requirements, such as SWL marking and compliance labelling, are documented in the Product Design Specification rather than in the QFD matrix, as they are mandatory compliance conditions rather than performance-driven customer differentiators.

3.2.3. Step 3: Determining the Relative Importance of the Requirements

Each customer requirement was assigned an importance rating between 1 and 10 (1 – not at all important, 10 – extremely important). Table 8 contains a list of the customer requirements and their associated importance ratings.

Table 8: End-effector customer requirements and importance ratings.

Customer(s)	Customer Requirement	Importance	Feature Type
Health & Safety / HSE	Zero red-category handling risks	10.0	Basic
Engineering / Manufacturing	Interfaces with existing lift control handle	9.0	Basic
Engineering / Manufacturing	Easily pivots between the horizontal and vertical planes	9.0	Basic
Production Operator	Operable by a single team member	8.0	Performance
Production Operator	Cycle time is maintained ≤ 212 s	8.0	Performance
Engineering / Manufacturing	Materials/structure can meet production lifetime volumes	9.0	Basic
Production Operator	System is easy to inspect	7.0	Performance
Maintenance Technicians	System is easy to maintain	6.0	Performance
Maintenance Technicians	System can operate 12 months without requiring thorough maintenance examination	9.0	Basic
Engineering / Manufacturing	Cost is kept within budget	6.0	Basic
Engineering / Manufacturing	The lift assist system provides a safe margin against structural overload	10.0	Basic
Engineering / Manufacturing	Load remains securely attached during lifting and positioning	10.0	Basic
Health & Safety / HSE	System provides real-time vacuum level feedback to the operator	8.0	Basic
Health & Safety / HSE	Working height is adjustable to accommodate the 5th percentile female to the 95th percentile male	8.0	Basic
Health & Safety / HSE	Design minimises excessive trunk flexion and torsion loading	8.0	Performance
Production Operator	Low manual effort to manipulate device	7.0	Performance
Health & Safety / HSE	System fails in a safe manner in the event of vacuum loss or power failure	10.0	Basic
Engineering / Manufacturing	System does not interfere with surrounding equipment or restricted zones	8.0	Basic

3.2.4. Step 4: Identifying and Evaluating the Competition

The fourth step involved assessing each customer requirement against competitor products using a 1–5 Likert scale (1 = requirement not met; 5 = requirement fully satisfied). The competitor products identified in Section 2.2.3 were benchmarked against these requirements, with the full results summarised in Appendix 8.11.

In instances where information was limited, certain requirements remained unassessed. Competitor products achieving high scores were subsequently analysed to identify potential design features for integration.

3.2.5. Step 5: Generating Engineering Specifications

This stage required identifying at least one quantifiable metric for every customer requirement. These metrics served as the engineering specifications, defining exactly how the design would meet user needs. When a requirement lacked a measurable parameter, it was flagged as ambiguous or poorly defined, prompting a re-evaluation to ensure that every design goal was verifiable.

3.2.6. Step 6: Relating Customers' Requirements to Engineering Specifications

The relationships between customer requirements and engineering specifications were evaluated using a 0–1–3–9 weighting scale (0 = none, 9 = strong). This enabled qualitative interactions to be converted into prioritised numerical values. Requirements without meaningful linkage to measurable specifications were refined or consolidated to maintain traceability within the QFD matrix, and several requirements were mapped to multiple specifications to reflect design interdependencies.

3.2.7. Step 7: Setting Engineering Specification Targets and Importance

The relative importance of each engineering specification was determined by calculating an absolute weight (A), defined as the sum of the products of the relationship values (R) and customer importance ratings (I), such that:

$$A = \sum (R \times I)$$

The resulting values were normalised against the total of all specification scores to produce a final priority percentage. This ensured that engineering effort was directed towards specifications with the greatest impact on customer satisfaction.

Assigning quantitative targets to each engineering specification is fundamental to the Product Design Specification, as these targets enable objective comparison of conceptual solutions and validation of the final detailed design. Many target values were derived from the literature review; however, several required additional analytical justifications.

For fatigue-critical structural members, the maximum operational stress was limited to a conservative fraction of the material yield strength, in accordance with fatigue design principles outlined in Shigley's (Nisbett and Budynas, 2024). This approach ensures that combined mean and alternating stresses remain within acceptable limits defined by the Soderberg and Goodman failure criteria.

From the calculated lift tube area and maximum vacuum of -44 kPa, the system generates 1119.8 N of lifting force. Applying a safety factor of 2 results in an allowable design load of 57 kg. The minimum vacuum required to support this load is -22 kPa. To prevent operation near the theoretical failure threshold, a three-stage monitoring system was defined: Green (-35 to -44 kPa, $\text{FoS} \geq 1.6$), Amber (-25 to -35 kPa, reduced safety margin), and Red (< -22 kPa, $\text{FoS} \leq 1$).

In accordance with ISO 11228-2 (ISO, 2007), sustained push/pull forces for frequent industrial tasks should not exceed approximately 60 - 70 N for female operators. To ensure inclusivity and minimise musculoskeletal risk, the lift assist was therefore specified to require ≤ 60 N sustained excitation force and ≤ 100 N peak starting force.

3.2.8. Identifying Relationships Between Engineering Specifications

Finally, the interrelationships between the engineering specifications were evaluated to identify technical dependencies and potential conflicts. This stage examines how improving one specification may positively or negatively influence another (e.g., increasing structural stiffness may increase mass, thereby affecting manual handling effort). By combining these interactions with the calculated specification importance ratings, informed design trade-offs can be managed systematically and transparently.

The completed QFD matrix, including the correlation “roof,” is presented in Figure 29.

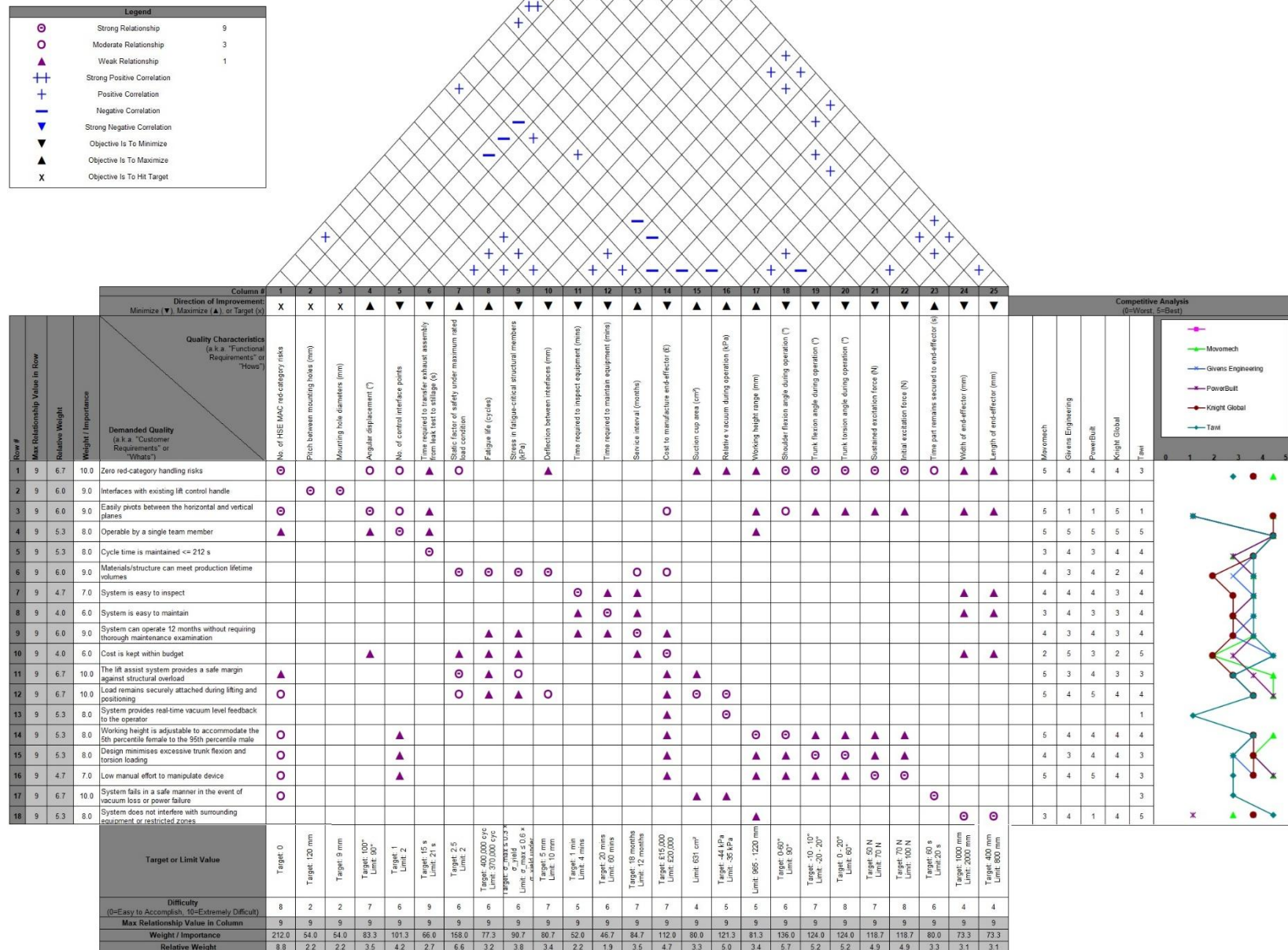


Figure 29: R31 end-effector QFD Matrix

3.3. Design Failure Mode & Effects Analysis (DFMEA)

DFMEA is a systematic approach used to pre-empt potential product failures, determine their effects on performance, and prioritise actions to mitigate risk. In contrast to Fault Tree Analysis (FTA), which is a top-down, deductive method used to trace the root causes of a defined system-level failure, DFMEA is a bottom-up, inductive approach that evaluates potential failure modes at the component and subsystem level before failures occur (Andy Prastyabudi, Faharga and Chandra, 2024). Similar to the QFD process, this DFMEA was conducted by a cross-functional team comprising the project manager, manufacturing engineer, quality engineer, and maintenance technician. This project followed the AIAG/VDA framework, which utilises an Action Priority (AP) methodology. This approach assigns Low, Medium, or High priorities for risk mitigation based on the interrelationships between Severity, Occurrence, and Detection ratings (AIAG and VDA, 2019). The complete DFMEA for this project is shown in Appendix 8.12; an extract is displayed in Figure 30.

Item	Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s)/ Mechanism(s) of Failure	Occurrence	Current Design Prevention Controls	Current Design Detection Controls	Detection	RPN	AP	Recommended Action(s)	Responsibility and Target Completion Date	Action Results				
														Severity	Occurrence	Detection	RPN	AP
Pivot Coupling	Pivot/rotate the exhaust from horizontal to vertical	Uncontrolled rotation (overshoot/swing). Rotation torque exceeds ergonomic limit → operator cannot complete rotate smoothly. Locking/positioning feature fails (if used).	- Misalignment / collision with stillage/leak tester - Operator strain - Increased cycle time	7	Insufficient damping/gear ratio	6	None	Measure maximum acceleration using smartphone attached to end effector	5	210	H	Mechanical damping to be designed into pivot to limit angular acceleration ($^{\circ}/s^2$)	M Ashe - 05/03/26	7	3	5	105	M
Main end-effector framework	Support and distribute load through structural frame	Structural yielding/bending under rated load.	- Misalignment of grippers	2	Poor weld joint geometry	4	None	Visual inspection of external weld quality	6	216	H	Weld design standards as per ISO 2553	M Ashe - 05/03/26	9	3	3	81	L
		Fatigue/weld crack at high stress joints. Fastener loosening → geometry shift.	- Catastrophic failure → dropped load	9	Inadequate torque spec for joints	6	None	Torque measurement verification during physical sign-off and 12-month inspection	4	216	H	Fastener torque derived using VDI 2230 joint analysis	M Ashe - 05/03/26	9	3	4	108	L

Figure 30: Extract from the DFMEA highlighting High Action Priority items requiring corrective action.

Following completion of the DFMEA using the AIAG/VDA framework, three High Action Priority items were identified due to insufficient design prevention controls, necessitating targeted mitigation actions.

① Uncontrolled rotation of the pivot mechanism was identified as a safety-critical failure mode. Mechanical damping was therefore specified to limit angular acceleration ($^{\circ}/s^2$) and reduce dynamic instability during operation. Verification of peak angular acceleration during prototype testing can be achieved using validated smartphone accelerometer measurements, providing a practical and cost-effective assessment method (Grouios et al., 2022).

② Poor weld bead geometry was also identified as a potential cause of structural failure. To strengthen prevention controls, weld specifications in accordance with ISO 2553 were introduced to clearly define weld type and size on manufacturing drawings (ISO, 2019). Joint integrity will be verified through macro-etch examination of representative weld samples to confirm penetration and throat adequacy.

③ Finally, inadequate torque specification for structural fasteners was highlighted as a potential contributor to joint slip or fatigue failure. Fastener preload values will therefore be derived using VDI 2230 joint analysis to ensure adequate clamp force and fatigue resistance under service loading (VDI, 2015).

3.4. Product Design Specification (PDS)

All requirements identified and justified in Sections 1, 2, and 3 were consolidated into a structured Product Design Specification (Appendix 8.13). The PDS formalises the functional, performance, safety, and manufacturing requirements and serves as the governing document throughout concept development, detailed design, verification, and commissioning.

4. Conceptual Design

4.1. Design Concepts

To generate feasible design solutions, the end-effector was decomposed into several functional subsystems, including the vacuum gripping mechanism, pivot mechanism, structural frame, and variant accommodation method. Multiple concepts were generated for each subsystem using hand sketches (Figure 31). This approach ensured a broad exploration of design possibilities while maintaining focus on the key functional requirements defined in the Product Design Specification. The concepts were subsequently organised in a functional concept matrix (Table 9) to systematically compare alternative design approaches. The resulting concepts represent distinct design philosophies with varying levels of complexity, adjustability, and manufacturability.

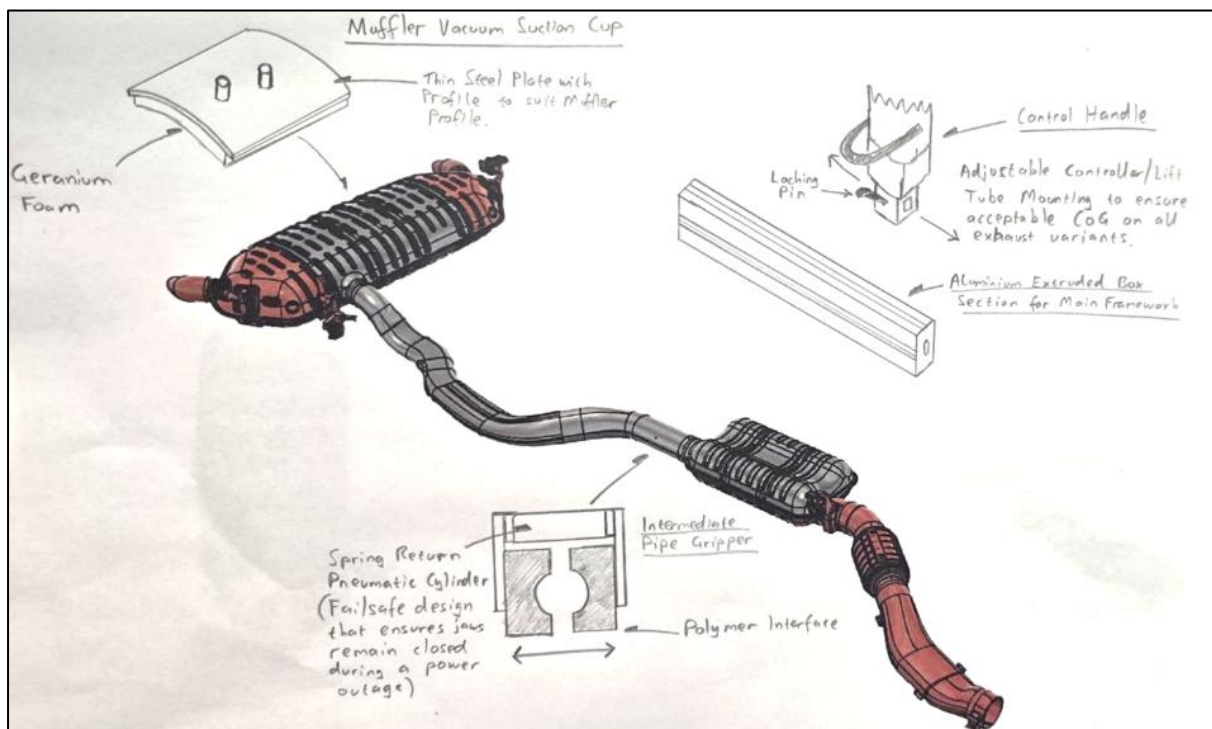


Figure 31: Example concept sketches.

Table 9: Functional concept matrix.

Function	Concept A	Concept B	Concept C
Rear Gripping Method	Dual silicone vacuum cups.	Dual metal vacuum cups with closed-cell foam interface.	Single metal vacuum cup with closed-cell foam interface.
Front Gripping Method	Pneumatic gripper cylinder.	Silicone resonator vacuum cup.	Cradle-type saddle.
Pivot Mechanism	Cartridge bearing pivot with manual rotation and remote-activated locking pin.	Single pivot with cartridge bearings. Rotated via pneumatic cylinder with push button.	Single pivot pin joint with a greased bush. Manually rotated. Mechanical locking pin with hand lever actuation.
Pivot Damping	Friction washer stack.	Rotary viscous damper.	Gas strut damper.
Variant Accomodation	Fixed geometry design.	Sliding control assembly for longitudinal adjustment.	Sliding ballast weight.
Structural Frame	Welded steel box section.	Aluminium extrusion with bolted joints.	Tubular steel with bolted joints.
Location Guides	Fixed bars that align with the edges of the rear muffler and resonator.	Tapered saddle that interfaces with the muffler inlet pipe and/or the resonator outlet pipe.	Integrate alignment features into the rear muffler suction cup(s).

4.2. Design Selection

To select the most appropriate concept for each subsystem, a weighted decision matrix approach was used. Evaluation criteria were derived from the PDS and included factors such as reliability, ease of operation, durability, weight, and manufacturing complexity. Each concept was scored against these criteria using a five-point scale, and weighted totals - based on the relative importance values derived from the QFD - were used to determine the most suitable design solution.

Many requirements defined in the PDS are not specific to individual functional concepts. For example, specification 9.6 limits trunk flexion during operation to a range of -20° to 20° , which all concepts can meet. Compliance with such requirements is instead ensured during the detailed CAD design of the end-effector.

The decision matrix for the rear gripping method is shown in Table 10, while the full set of decision matrices is provided in Appendix 8.14.

Table 10: Rear gripping method decision matrix.

Criteria	Weighting	Rear Gripping Method Concepts		
		Dual silicone vacuum cups	Dual metal vacuum cups with closed-cell foam interface	Single metal vacuum cup with closed-cell foam interface
Gripping Reliability	0.40	1.2	2	1.2
Durability and Maintainability	0.25	0.5	1	1
Manufacturing Cost and Complexity	0.20	1	0.6	0.8
Weight	0.15	0.75	0.6	0.6
Total Weighted Ratings		3.45	4.2	3.6

The primary evaluation criteria for the front and rear gripping methods were gripping reliability, durability, and maintainability. For the rear muffler, dual metal vacuum locations with a closed-cell foam interface were ranked as the preferred solution due to the durable interface material and the additional safety redundancy provided by incorporating two suction cups rather than one. A vacuum suction method was considered unsuitable for the front resonator due to the limited surface area available for engagement. Instead, the cradle-type saddle scored higher than the pneumatic gripper cylinder due to its improved durability and lower cost.

The key evaluation criteria for the pivot mechanism concepts were ease of operation, motion control, and stability. The cartridge bearing design with pneumatic actuation ranked highest for ease of operation due to the minimal effort required from the operator. However, the cartridge bearing with a manually activated locking pin achieved the highest overall score due to its lower maintenance requirements and reduced implementation cost.

Three damping concepts were proposed to control the angular acceleration when pivoting between the horizontal and vertical planes (Figure 32). The friction washer stack scored lowest due to its limited motion control capability and higher maintenance requirements. The rotary viscous damper and gas strut scored similarly across motion control, stability, durability, and maintainability. However, the rotary viscous damper was ultimately preferred due to its more compact design.



Figure 32: Pivot damping mechanisms (Stromag, 2024; RS Components, 2026a, 2026b).

The variant accommodation concepts were evaluated based on stability, ease of adjustment, packaging and integration, and manufacturing cost and complexity. Stability was given the highest weighting due to the requirement to maintain the exhaust orientation within the 15° maximum angular deviation specified in the PDS. The sliding ballast weight concept achieved the highest overall weighted score, outperforming the sliding control assembly and fixed geometry designs.

The structural framework forms the primary load-bearing structure of the end-effector and was therefore evaluated against criteria including strength, rigidity, and weight, in accordance with the requirements specified in the PDS. A welded steel box-section frame was selected over aluminium extrusion and tubular steel designs with bolted joints, as it provides greater structural rigidity through continuous welded connections and closed-section members. Secondary advantages include reduced assembly complexity and improved long-term durability compared with bolted alternatives.

Ensuring the lift-assist operator can easily and accurately locate the end-effector on the exhaust assembly is essential for minimising the cycle time of the product transfer operation. Three design concepts were therefore evaluated against criteria including locating effectiveness and ease of operation. Figure 33 illustrates the tapered saddle design, selected over steel bars, and the alignment features integrated into the rear muffler suction cups, providing a compact yet effective engagement solution.



Figure 33: Tapered saddle concept design for end-effector/part alignment.

Based on the concept selection process, the final end-effector architecture incorporates dual metal vacuum cups with a foam interface, a cartridge bearing pivot with manual locking, a rotary viscous damper for motion control, a sliding ballast weight for variant accommodation, a welded steel box-section structural frame, and a tapered saddle alignment guide. These concepts collectively satisfy the functional, ergonomic, and safety requirements defined in the Product Design Specification.

4.3. Design Development

Initial three-dimensional CAD models were developed for the primary components of the vacuum lift assist end effector to verify packaging, functional interfaces, and overall feasibility prior to detailed design (Figure 34). The models were created in Autodesk Fusion 360 and represent the key subsystems identified during the concept selection stage, including the vacuum suction cup assembly, main structural member, intermediate pipe support, pivot mechanism, and alignment fixture. These components, collectively, form the core architecture of the end-effector and establish the spatial relationships required for the safe handling of the exhaust assembly.

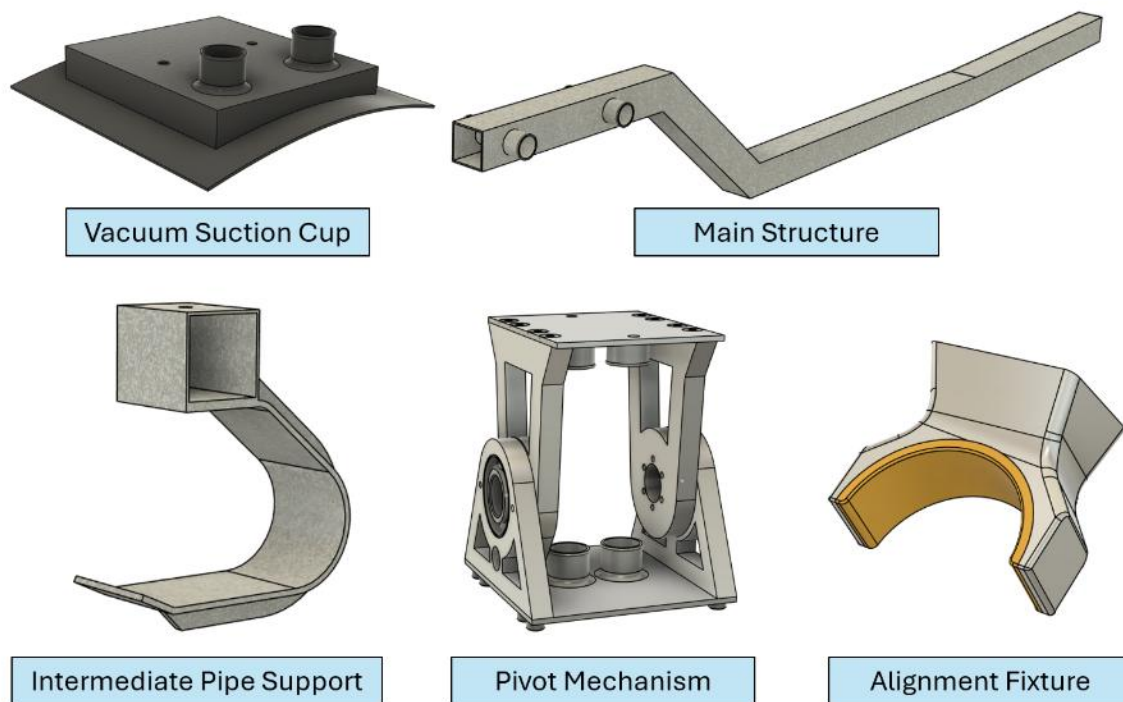


Figure 34: Primary end-effector components modelled in CAD.

The vacuum suction cup model was created to define the mounting interface, pad spacing, and compliance with the curved muffler geometry. The main structure was modelled using box-section members to reflect the selected welded-steel-frame concept, providing an initial assessment of stiffness, reach, and clearances. An intermediate pipe support was incorporated to stabilise the exhaust during lifting and reduce rotational movement caused by the offset centre of gravity.

A pivot mechanism assembly was also developed to allow rotation of the exhaust between horizontal and vertical orientations, consistent with the functional requirements defined in the Product Design Specification. Figure 35 illustrates a clash condition with the pivot mechanism, necessitating a redesign of the structure. Finally, an alignment fixture was modelled to assist operators in quickly and repeatably locating the end effector on the exhaust assembly. These preliminary models enabled early evaluation of component interaction, mass distribution, and manufacturability before proceeding to detailed analysis and refinement.

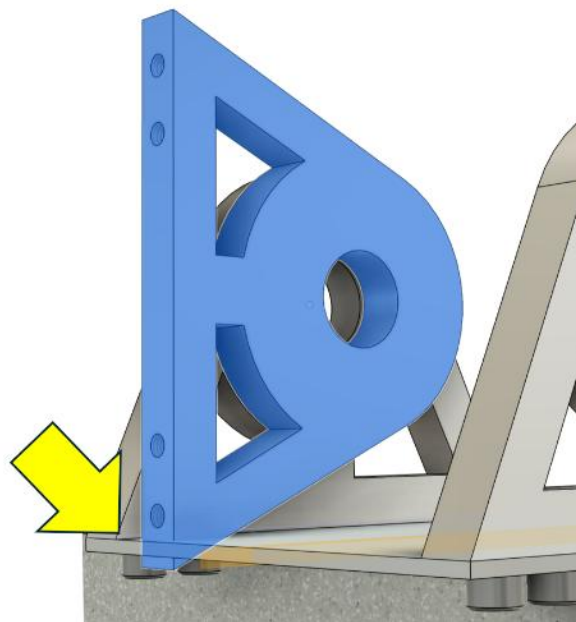


Figure 35: Pivot mechanism clash condition.

4.4. Material and Manufacturing Process Selection

Material and manufacturing process considerations were evaluated concurrently with the CAD design development described in Section 4.3, as these factors directly influenced component geometry, structural layout, and manufacturability. However, the final material selections and process justifications are presented separately in this section to improve clarity and discussion flow. Materials and manufacturing processes were selected for each bespoke end-effector component using a performance-based approach, guided by Ashby's methodology (2025) to prioritise structural members based on stiffness-to-weight indices ($M = E^{1/2}/\rho$). For the main structure and intermediate pipe support, Galvanised Steel was identified as the optimal material; while the Ashby chart in Figure 36 confirms that materials like CFRP and aluminium offer superior performance indices, steel provides a necessary compromise between a high Young's modulus, industrial durability, and significantly lower cost (Nisbett and Budynas, 2024). Furthermore, this selection leverages the material's excellent MIG weldability, allowing for a rugged frame that can withstand the rigours of a factory environment more effectively than lighter, more brittle alternatives.

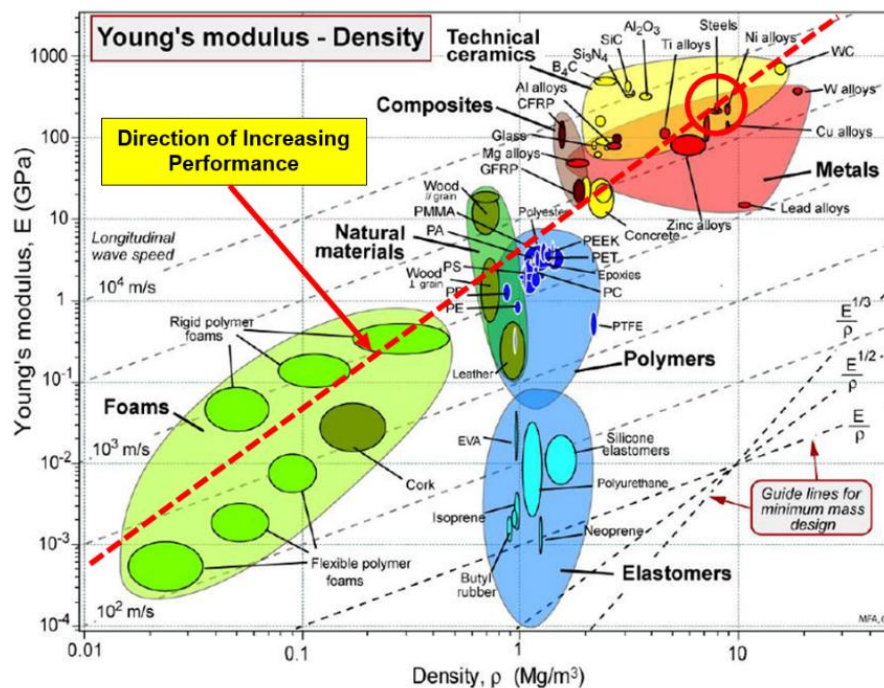


Figure 36: Ashby chart for Young's modulus vs. density showing the selection criteria for the end-effector's primary structural frame (Ashby, 2025).

Low-carbon steel was chosen for the vacuum suction cup frame due to its high ductility and suitability for TIG-welded fabrication, ensuring the airtight joints required for vacuum integrity. Conversely, the pivot mechanism utilises an aluminium framework to minimise mass at the end of the lift tube, improving ergonomics and reducing inertial loading, while Stainless Steel (AISI 304) was selected for the base plates to provide superior wear resistance at bearing interfaces. Aluminium alloys provide high specific stiffness, making them advantageous for such weight-sensitive assemblies (Ashby, 2025).

For sealing, EPDM (Ethylene Propylene Diene Monomer) closed-cell foam was selected for its high conformability to irregular muffler profiles, consistent with elastomer selection guidelines for sealing applications (Harper, 2002). The alignment fixture incorporates Acetal resin (POM) at the exhaust interface to provide a low coefficient of friction and prevent surface marring. Manufacturing processes were optimised for industrial scalability, utilising MIG/TIG welding for framework, CNC machining for high-tolerance features such as the pivot bearings, and laser-cut profiles where appropriate. A full list of the materials and processes is shown in Table 11.

Table 11: Materials and manufacturing processes selection table.

Component	Function	Material Selected	Alternative Materials Considered	Manufacturing Process	Justification	Finish / Post-Processing
Main Structure	Primary load-bearing frame.	Galvanised Steel	Aluminium; Stainless Steel; Mild Steel	Cut, mitre joints, weld (MIG) together	- Cost-effective for weight to strength ratio. - Good corrosion resistance.	Cold-galvanised spray on weld joints
Vacuum Suction Cup	Rigid structure to support the vacuum seal and the exhaust.	Low-Carbon (Mild) Steel	Stainless Steel	Cut, cold form profiles, weld (TIG) together	- Cost-effective for weight to strength ratio. - Good formability	Powder coated black
Vacuum Suction Cup Seal	Provides a seal between the exhaust and suction cup	EPDM Closed-Cell Foam	Silicone Foam; Polyurethane Foam	Cut to size using template	- Low cost - High conformability for irregular muffler shell profile.	Mount using high-bond pressure sensitive adhesive (PSA) tape
Pivot Mechanism Structure	Enables the end-effector to pivot between horizontal and vertical planes.	- Framework: Aluminium - Upper & lower bases: Stainless Steel AISI 304	One-Piece Machine Billet Aluminium; Mild Steel	- Framework: Machined using a CNC milling machine. - Upper & lower bases: Laser cut profile and bolt holes. CNC-machined hose bosses, MIG-welded onto baseplates.	- Framework: Provides high stiffness-to-weight ratio and high precision for bearing locations. - Upper & lower bases: High-strength.	N/A
Intermediate Pipe Support	Mechanical fixture to support the front mass of the exhaust.	Galvanised Steel	Stainless Steel	Cut, cold form profiles, weld (MIG).	Heavy-duty structural support for offset loads while ensuring corrosion resistance.	Cold-galvanised spray on weld joints
Alignment Fixture	Aids with aligning the vacuum suction cups into the correct position.	- Support Structure: Aluminium - Exhaust Interface: Acetal Resin	- Support Structure: Stainless Steel; Mild Steel - Exhaust Interface: Nylon 6/6 (Polyamide); PTFE-Filled Delrin (Delrin AF)	- Support Structure: Machined using a CNC milling machine. - Exhaust Interface: Machined using a CNC lathe.	- Support Structure: Provides high stiffness-to-weight ratio - Exhaust Interface: Low coefficient of friction prevents marking/scratching of the exhaust pipe and allows for smooth "glide-on" engagement.	Mount to support structure using high-bond adhesive.

5. Detailed Design

5.1. 3D Model Assembly

The development of a comprehensive 3D assembly in Autodesk Fusion 360 served as a critical design verification stage to ensure the successful integration of bespoke components and commercial off-the-shelf (OTS) parts. As illustrated in Figure 37, the model was used to verify functional interfaces and precise alignment between the end-effector and the complex exhaust geometry. Spatial analysis, shown in Figure 38, confirmed that the assembly maintains necessary clearances with the leak test machine and finished goods stillage, mitigating collision risks.

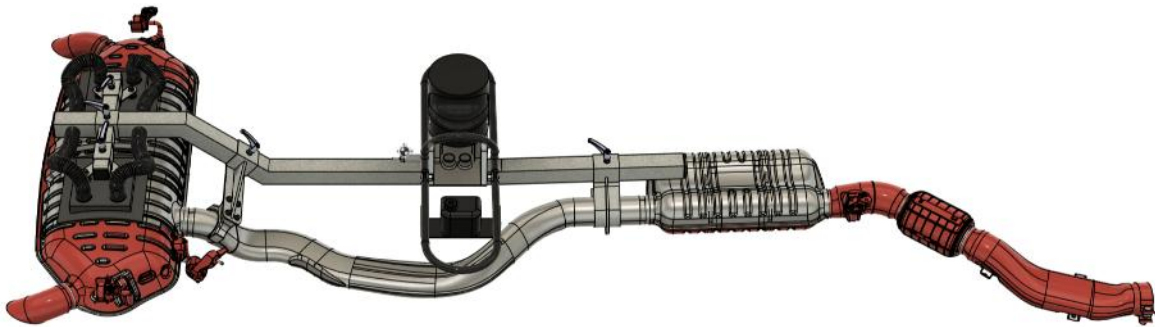


Figure 37: 3D model of the 1st end-effector assembly design.

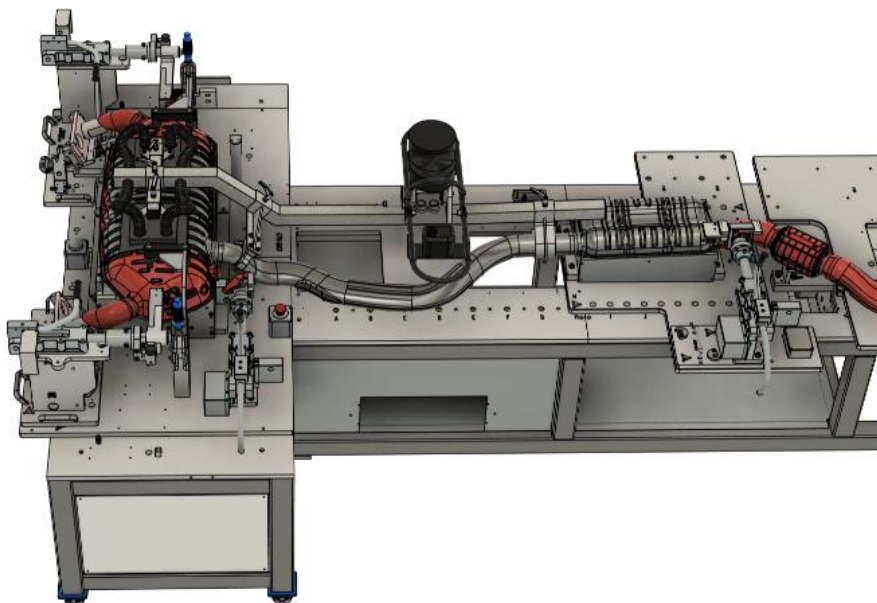


Figure 38: 3D end-effector/leak tester clearance check.

To optimise cost-effectiveness, several high-specification OTS components were integrated, including 7206-B-2RS pivot bearings, a two-way viscous damper, and a remote-activated locking pin controlled via a mechanical brake lever. Adjustable clamping levers were utilised to enable positional flexibility for the vacuum cups and mechanical supports (Figure 39). This virtual assembly validates the core architecture and ensures successful interfacing with the vacuum control handle before proceeding to detailed structural analysis.

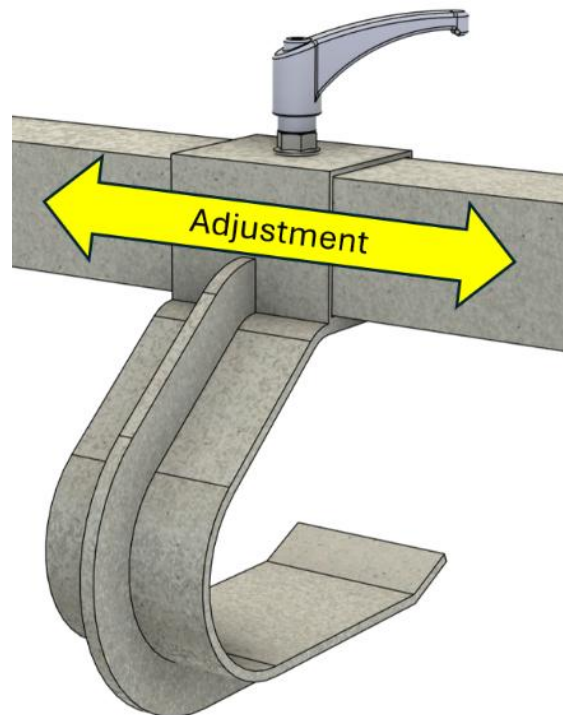


Figure 39: Clamping lever implementation to allow positional flexibility.

5.2. Design Verification

This section verifies that the end-effector satisfies the physical and performance requirements defined in the Section 3.4 (Product Design Specification). A primary challenge was mass reduction; the initial design was 22.16 kg, requiring a 4.16 kg reduction to meet the 18 kg limit. Dimensional constraints were satisfied, with a final width of 1711 mm and length of 623 mm, both within the allowable envelope. Furthermore, the combined suction cup area of 654 cm² exceeds the minimum of 631 cm² calculated in Section 2.2.4. This target assumed the vacuum supported the full exhaust load; as the mechanical support carries half the mass, the actual factor of safety is significantly higher than required, ensuring high operational reliability.

The equilibrium orientation of the end-effector was determined by analysing the centre of mass (CoM) location relative to the pivot axis. Theoretically, the assembly rotates until the CoM lies vertically below the pivot, at which point the resultant gravitational moment is zero. The equilibrium angle was calculated to be 33° (Figure 40), exceeding the maximum allowable angle specified in the PDS by 18°. This discrepancy indicated a significant imbalance that needed to be addressed by shifting the pivot mount across the X-axis by at least 81 mm.

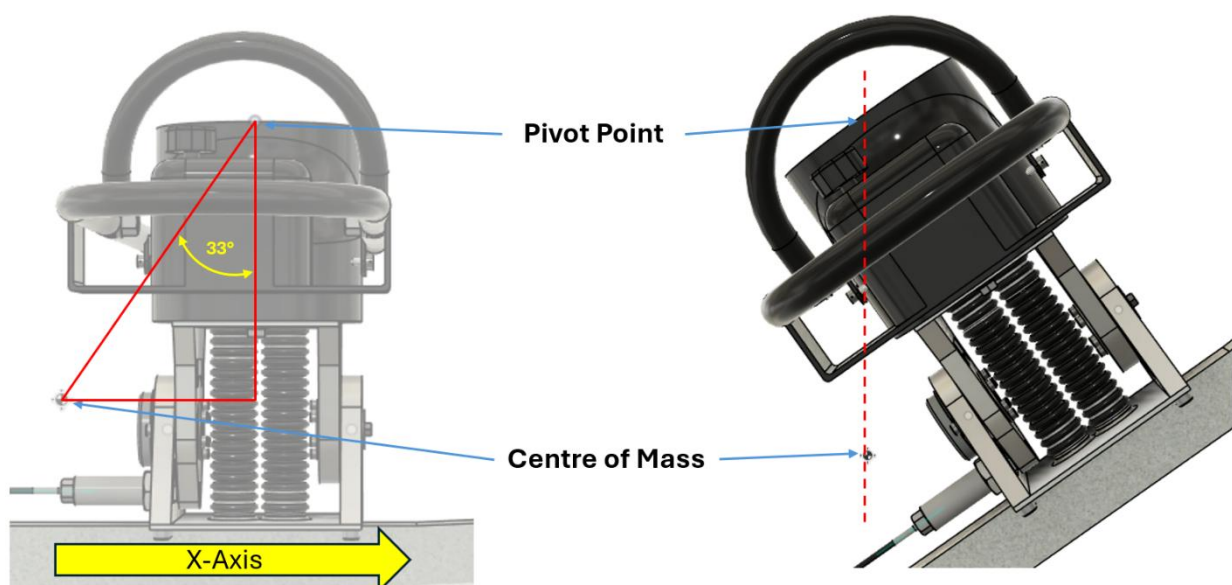


Figure 40: End-effector equilibrium angle.

A static structural simulation was conducted to evaluate stress and deflection under worst-case loading. Loads representing the 27 kg exhaust assembly were applied to the suction cup interfaces, producing 64 N downward force at each pad, with an additional 128 N applied at the mechanical pipe support. Contact conditions were defined between all interfacing components. The assembly was discretised using a finite element mesh to enable numerical approximation of the stress distribution (Figure 41). Fusion 360 automatically scaled the mesh size across components based on geometric complexity, applying finer elements in regions with small features and coarser elements in larger structural members to balance accuracy and computational efficiency (Logan, 2017).

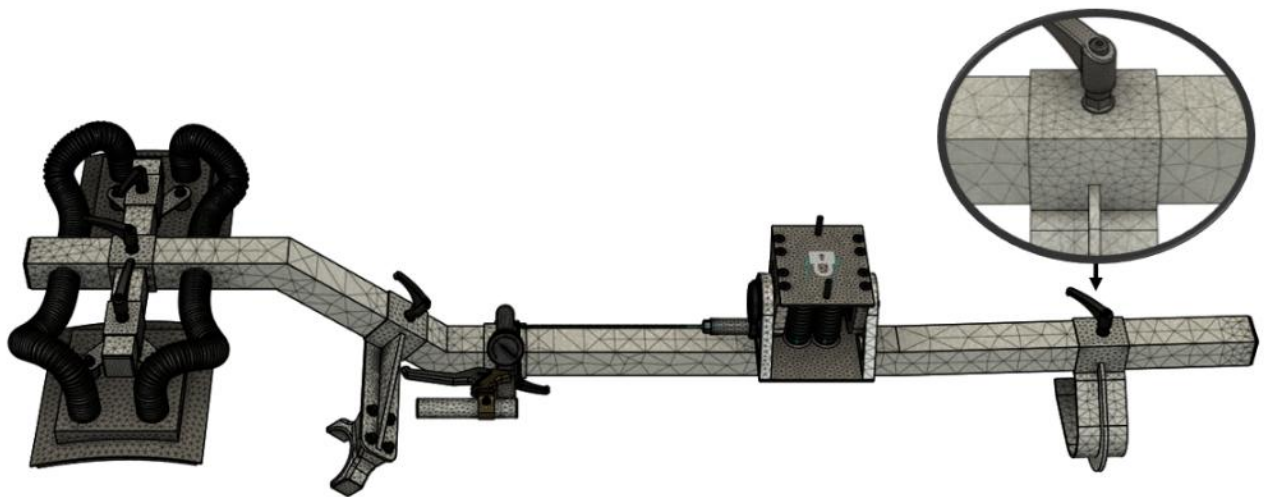


Figure 41: Discretisation of the end-effector assembly into a finite element mesh for structural analysis.

The results confirmed high safety factors across all critical components. The maximum observed displacement was 2.2 mm, significantly below the 10 mm limit discussed in Section 3.4. As illustrated in Figure 42, the peak stress of the galvanised frame was 51.1 MPa, remaining safely below the 124.2 MPa design limit ($0.6 \times \sigma_y$). Similarly, the aluminium pivot structure exhibited a peak stress of only 16 MPa - considerably below the 275 MPa limit - revealing opportunities for further weight reduction. Fastener analysis for the M8 8.8 bolts revealed a maximum stress of 20 MPa, representing a negligible fraction of the 640 MPa yield strength.

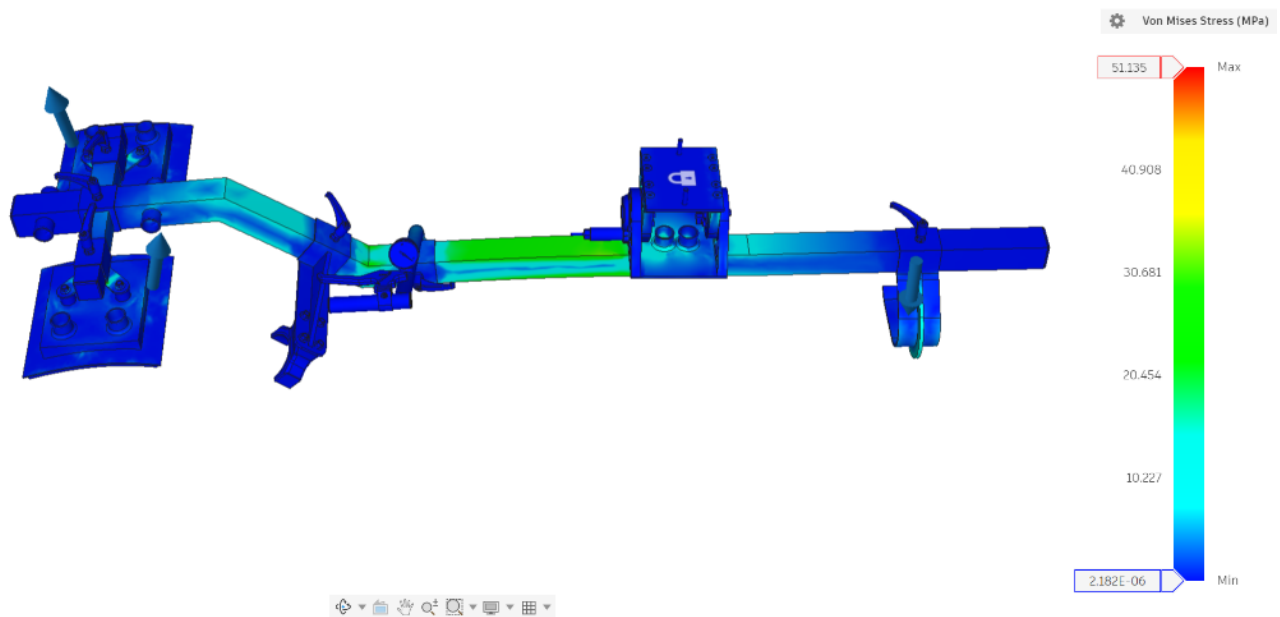


Figure 42: Predicted Von Mises stress distribution across the end-effector assembly under maximum exhaust load.

While the structural requirements were satisfied, the high safety margins identified in the primary framework and fasteners suggested an opportunity for further mass optimisation, which is addressed in the design iteration section.

5.3. Ergonomic Assessment

To evaluate the human-machine interface, a digital human model (Design Neta, 2017) was integrated into the leak-test and stillage environments (Figure 43). This simulation enabled a proactive assessment of postural demands against the established ergonomic criteria in the PDS.

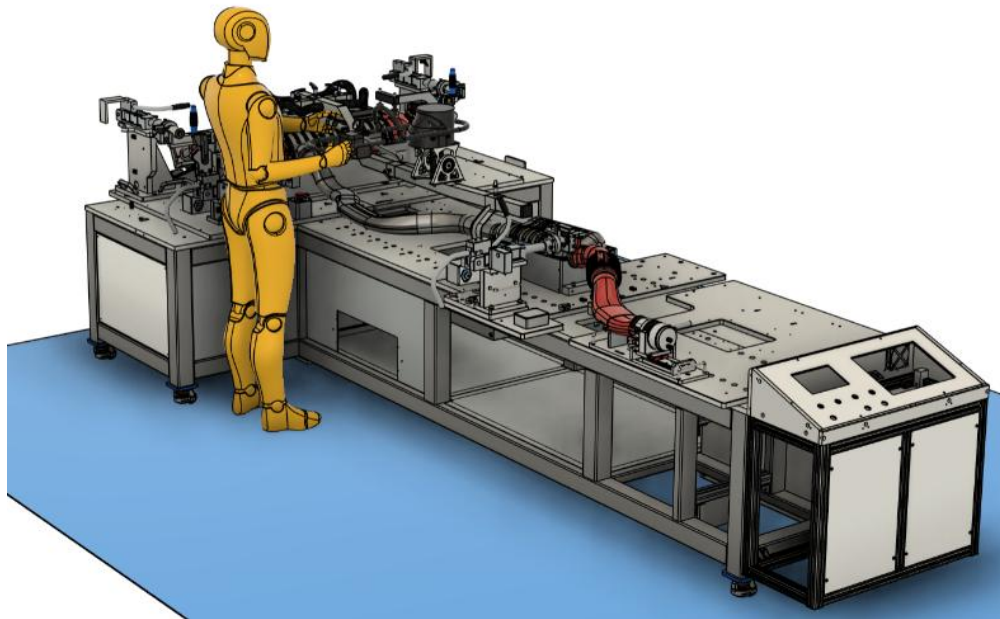


Figure 43: Ergonomic assessment of the human-machine interface within the leak test station environment.

The analysis primarily focused on working height and joint articulation. The initial design included a vacuum control handle height of 1180 mm, which fell within the recommended range of 965–1220 mm. However, this sat near the upper threshold, potentially leading to excessive shoulder flexion in smaller operators (5th percentile). To optimise the design for a broader user demographic, the iteration phase will aim to reposition the handle closer to the 1090 mm midpoint.

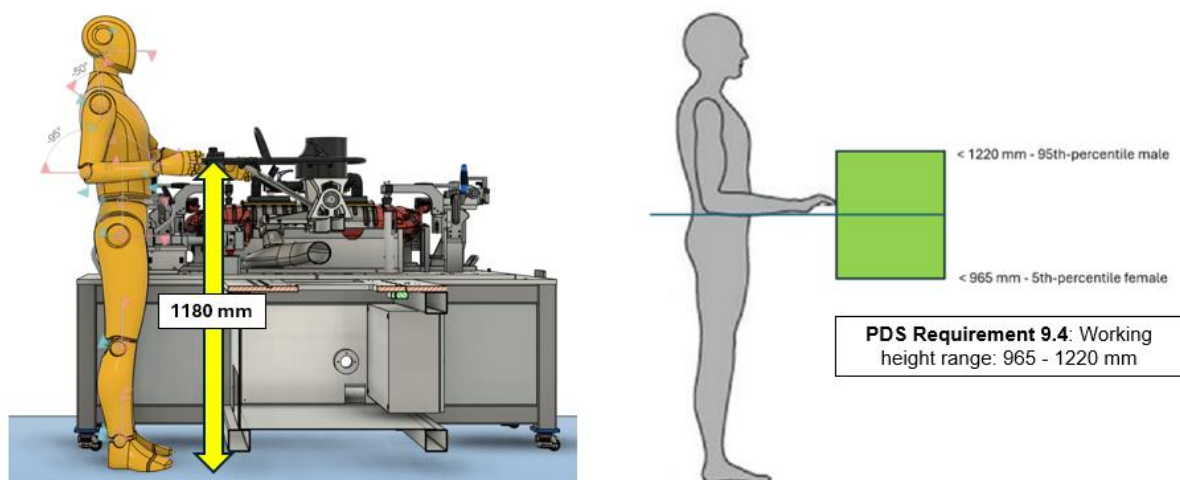


Figure 44: Ergonomic validation of vacuum controller positioning relative to the 5th-95th percentile working height envelope.

Despite the height concerns, postural results were positive: peak shoulder flexion reached only 50° (considerably lower than the 90° limit), and trunk flexion was measured at 15° (Figure 45), significantly under the 60° maximum. Certain dynamic ergonomic factors, including trunk torsion and excitation forces, remained outside the scope of the virtual CAD-based assessment. Trunk torsion could not be accurately evaluated due to limitations associated with the ergonomic analysis tools available within the CAD software. Furthermore, excitation forces, targeted at <100 N initial and <70 N sustained, are heavily influenced by the characteristics of the existing gantry system and therefore cannot be reliably predicted through simulation alone. Verification of these forces will require physical testing using a force transducer following the manufacture and integration of the end-effector with the lifting system.

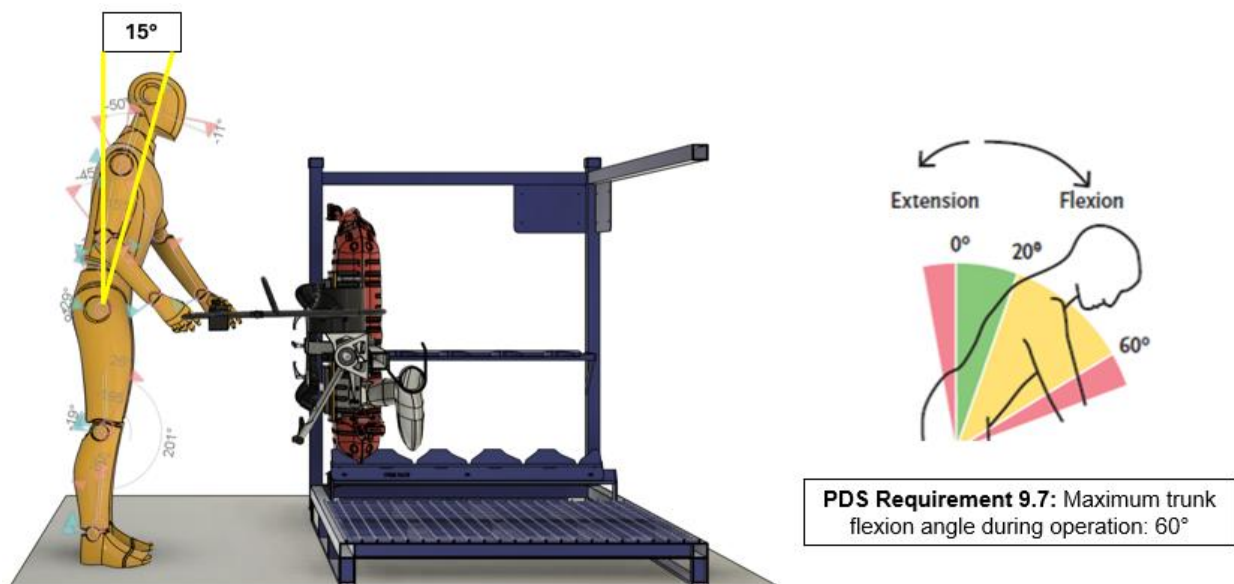


Figure 45: Validation of operator trunk flexion posture during stillage loading operations.

5.4. Design Iteration

As discussed in Section 2.1.2, initial product concepts rarely satisfy all design requirements, necessitating iterative design refinement. During the design verification and ergonomic assessments, several issues were identified. These are collated in Table 12, together with the proposed corrective actions implemented to resolve them.

Table 12: Identified design issues and proposed corrective actions.

Source of Requirement	Identified Issue	Proposed Action(s)
5.2 Verification	Mass of assembly exceeds 18 kg limit by 4.16 kg.	1) Remove 8 fasteners from the pivot mounting baseplates. 2) Refine the structural profiles of the pivot mounts and framework to achieve further mass reduction. 3) Add fillets to reduce stress in acute angled regions.
5.2 Verification	Equilibrium angle exceeds 15° limit by 18°.	Offset the pivot mounting mechanism by at least 81 mm along the global x-axis of the CAD assembly
5.3 Ergonomics	Controller handle height is biased towards the upper threshold. Limit: 1220mm. Actual: 1180 mm.	Reduce the distance between the pivot mounting baseplates.

The initial height of the pivot mechanism was selected to ensure sufficient clearance between the structural members throughout the rotational travel of the assembly. To achieve the required equilibrium angle, the pivot mounting baseplate and left-hand handle assembly were repositioned 85 mm closer to the rear muffler suction cups. As illustrated in Figure 46, additional modifications were incorporated into the pivot mechanism, including reducing the fastener count, removing material, adding fillets to reduce stress concentrations, and reducing the spacing between the mounting plates by 40 mm.

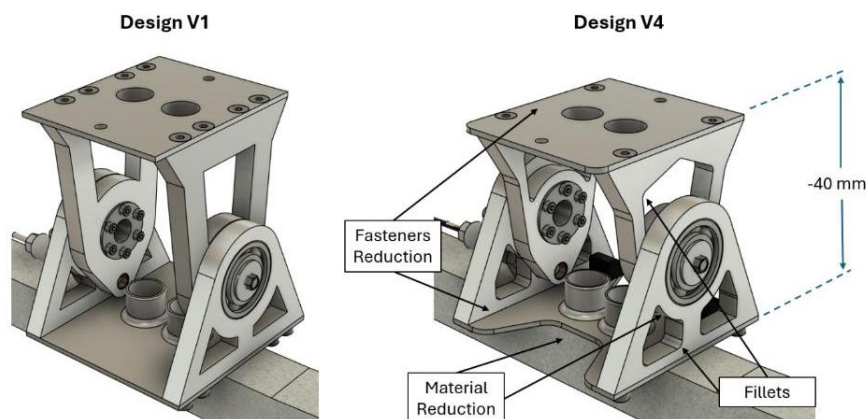


Figure 46: Evolution of the pivot mounting mechanism design.

Further mass optimisation was achieved by reducing the material thickness of the galvanised steel box sections and muffler suction cup structures from 2 mm to 1.5 mm (Figure 47). These changes reduced the total end-effector mass from 22.16 kg to 17.9 kg, satisfying the 18 kg design requirement.

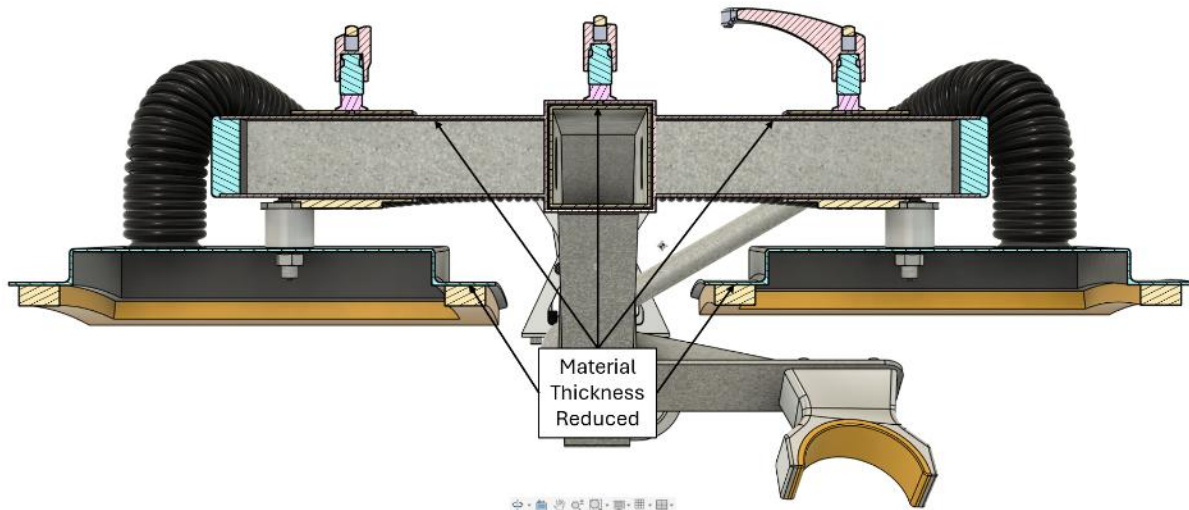


Figure 47: Sectional analysis of structural profiles highlighting strategic wall thickness reduction for mass optimisation.

A total of four design iterations were completed. Static stress analysis of the final design (V4) showed the peak stress increased from 51.1 MPa to 83.2 MPa, remaining below allowable limits. Maximum displacement increased from 2.2 mm to 2.9 mm (Figure 48), substantially below the 10 mm requirement, confirming compliance with the PDS.

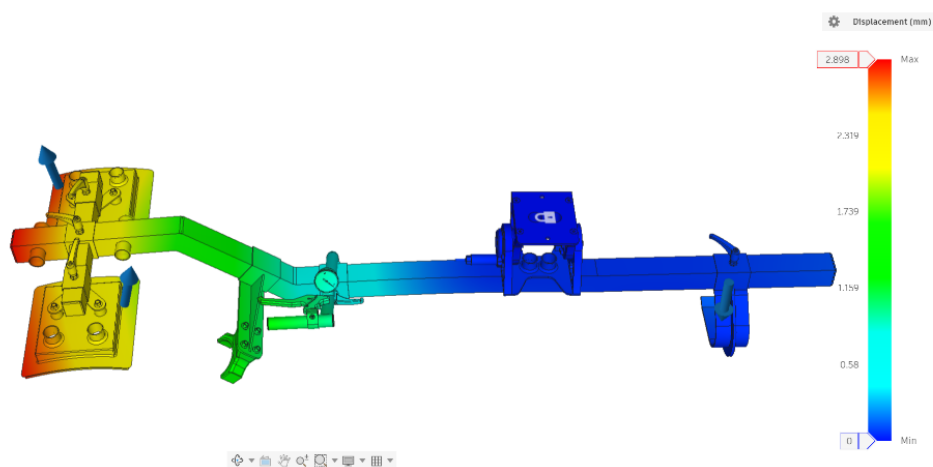


Figure 48: Predicted displacement across the end-effector assembly under maximum exhaust load.

Following the successful completion of design iterations and re-verification, the 3D model was finalised for issuance to potential suppliers. However, the bespoke components illustrated in Figure 49 required the generation of 2D technical drawings as a prerequisite for production. These drawings serve as the definitive specification for the manufacturing phase, detailing the essential dimensions, tolerances, and surface finishes required to ensure assembly fit and functional performance. The 2D engineering drawing for the main structure is presented in Figure 50.

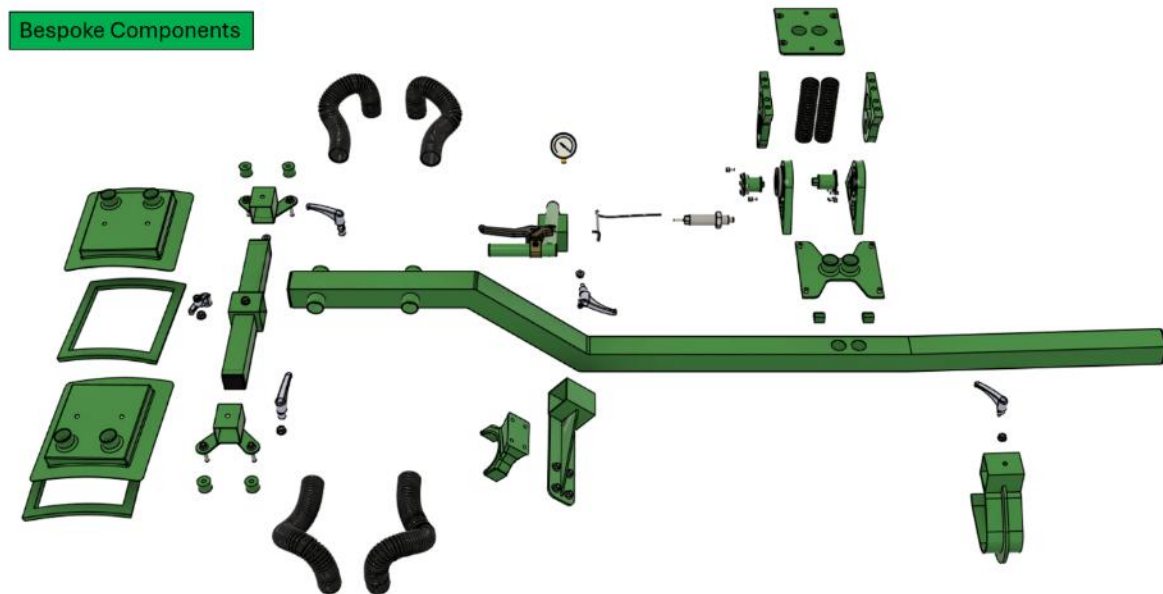


Figure 49: Component breakdown of the vacuum end-effector; green shading denotes bespoke fabricated elements requiring custom manufacturing.

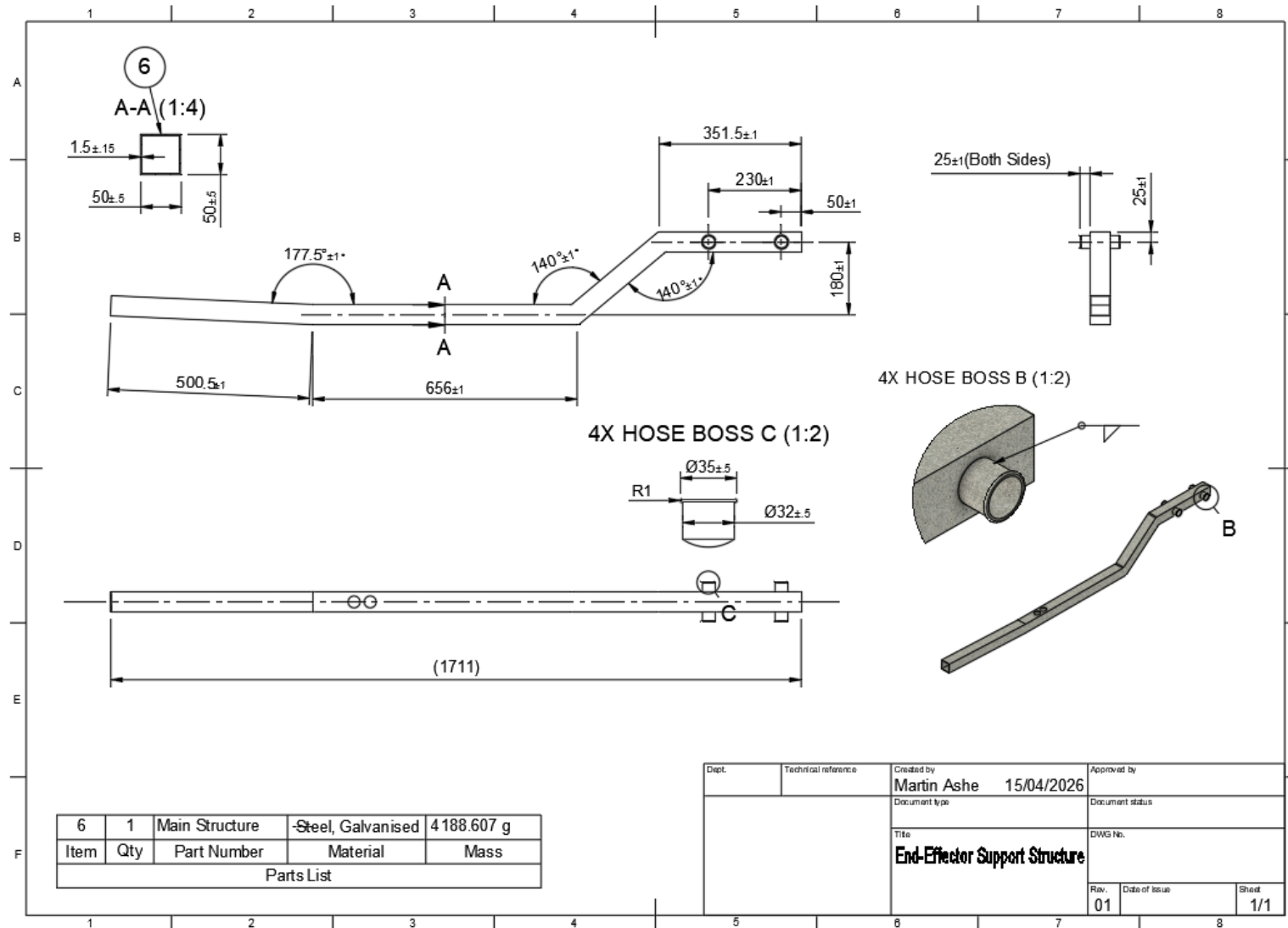


Figure 50: 2D drawing of the main end-effector structure.

5.5. Manufacturing Quotation

Manufacturing quotations were obtained from three potential suppliers: Cruz Engineering, CES, and JG Lifting. Each supplier received a technical data package containing detailed 3D CAD models, fully dimensioned 2D engineering drawings, and annotated assembly images to convey the end-effector's design intent, critical interfaces, and assembly requirements (Figure 51).

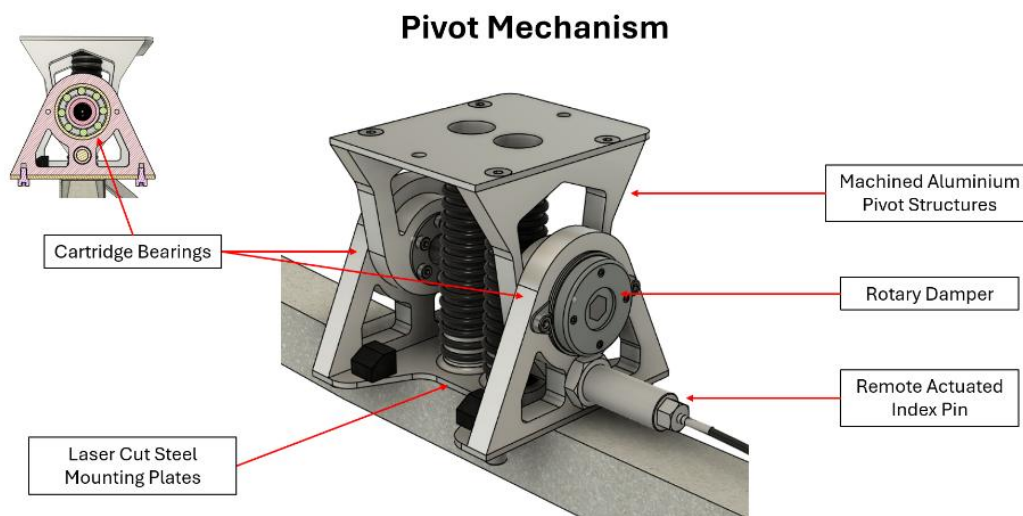


Figure 51: Annotated assembly of the pivot mechanism.

Quotations were assessed against key criteria, including cost, manufacturing capability, lead time, experience, and support/communication, using a weighted decision matrix (Figure 52). Although JG Lifting provided the lowest quotation cost (£7,675), CES achieved the highest overall weighted score (4.15/5) due to its strong manufacturing capability, shorter lead time, and established working relationship with Tenneco Highpoint. Consequently, CES was selected as the preferred manufacturing supplier.

Criteria	Weighting	Potential Manufacturing Suppliers		
		1 - Cruz Engineering	2 - CES	3 - JG Lifting
Cost	0.40	2	1.6	2
Manufacturing Capability	0.20	0.45	0.6	0.45
Lead Time	0.15	0.8	1	0.8
Experience	0.15	0.45	0.45	0.6
Support / Communication	0.10	0.3	0.5	0.1
Total Weighted Ratings		4	4.15	3.95

Figure 52: Weighted decision matrix for the selection of the manufacturing supplier.

6. Business Case Review

The business case for the vacuum lift assist system centres on employee safety, long-term operational efficiency and risk mitigation. Implementing the solution yields significant qualitative benefits, including improved employee morale and a positive corporate image for customers and suppliers. Financially, the project negates £85,000 in annual costs currently incurred due to the requirement for a second operator and overtime on Robot 31, where cycle times have slipped to 255 seconds (14 PPH). Furthermore, it severely reduces the risk of musculoskeletal injuries, potentially avoiding work-related ill-health costs, which averaged £21,500 per case in 2022/23.

These savings are balanced against a capital investment of £8,325 and an estimated annual electrical cost of £5,400 (Gallizzi, 2025). The transition to a vacuum-assisted process results in a 93% reduction in direct annual operating expenditure. Consequently, the project achieves a rapid break-even point within the first two months of operation, as illustrated by the cumulative cash flow in Figure 53. While the cycle time is projected to revert to the target 212 seconds (17 PPH), this remains subject to final installation validation. Presented to the Tenneco senior management team on 7th May 2026, this comprehensive assessment secured formal approval for the project to proceed to the manufacturing phase.

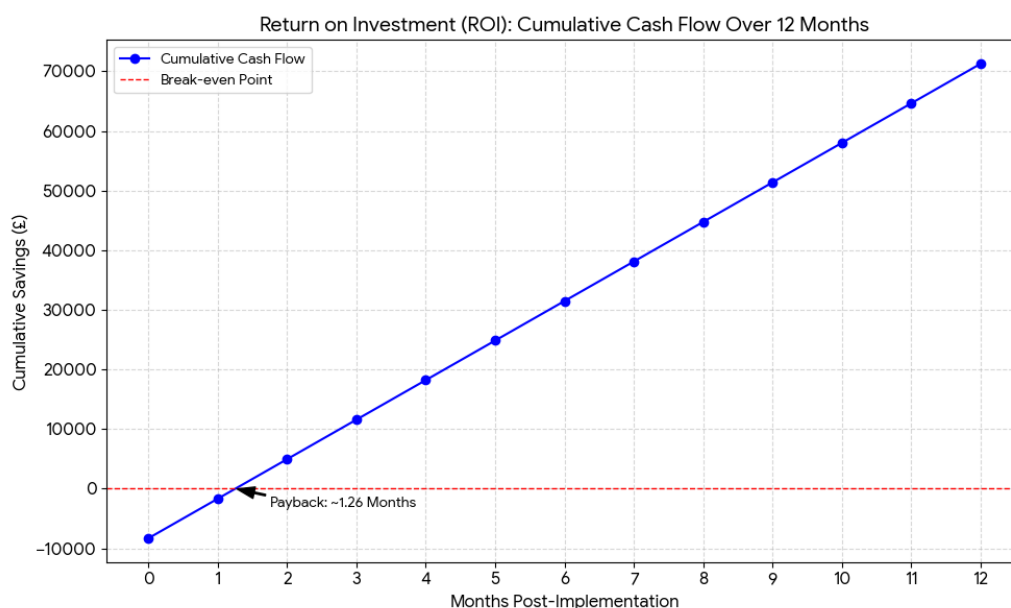


Figure 53: Return on Investment chart.

7. Conclusion and Recommendations for Future Work

7.1. Conclusion

This project successfully achieved its core aim of designing, developing, and validating a bespoke vacuum lift-assist end effector for handling the P6 MHEV automotive exhaust system at Tenneco Highpoint. Developed through a structured mechanical design framework, the finalised end effector design integrates into the plant's pre-existing vacuum-assisted gantry infrastructure. Crucially, the design eliminates all HSE red-category manual handling risks and transitions the cell back to an efficient single-operator process.

However, during execution, the forecasted timelines for certain project tasks were underestimated, causing the project to fall behind the initial schedule. Despite these timeline challenges, the final design satisfied the primary Product Design Specification (PDS) requirements relating to structural performance, ergonomics, dimensional constraints, and manufacturability. Finite element analysis verified structural integrity under maximum physical loads. Certain specifications discussed in Section 5.3, such as the trunk flexion and excitation forces, could not be verified until the system is implemented.

A competitive bidding process was conducted using three external suppliers, with CES selected as the preferred supplier following a weighted decision matrix assessment. Financially, the project delivers a projected direct annual cost saving of £85,000 by negating premium overtime hours, achieves full capital payback within 1.25 months, and avoids significant work-related musculoskeletal injury liabilities. Following this comprehensive assessment, the Tenneco senior management team formally approved the design for the manufacturing phase.

7.2. Recommendations for Future Work

Future work should focus on further weight optimisation, as indicated by the high Factor of Safety discussed in Section 5.4.1, followed by the physical manufacture and validation testing of the final design within the production environment. This should include safe working load testing, fatigue testing of the pivot mechanism, and verification of the predicted 212-second production cycle time. Investigations into more energy-efficient vacuum pump solutions, such as variable-speed systems that adjust motor output according to load demand, could further reduce operating costs.

A key lesson learned throughout the project was the importance of conducting detailed risk assessments following process changes involving manual handling operations. Prior to this project, the ergonomic implications of the modified Robot 31 process had not been fully assessed, contributing to the handling difficulties identified during the investigation. Future manufacturing process changes should therefore include formal ergonomic and manual handling assessments at the implementation stage to minimise operator risk and prevent similar issues.

The implementation of a robust maintenance strategy, initially based on predictive and preventative practices, would ensure the equipment continues to operate safely and efficiently. Finally, long-term ergonomic assessments should be conducted following implementation to evaluate operator feedback, usability, and overall effectiveness during continuous production use.

8. Appendices

8.1. MAC Lifting Assessment Report

Manual handling lift assessment for the P6 MHEV exhaust system, as discussed in Section 1.2, summarising key ergonomic risk factors and recommended control measures such as the installation of a vacuum lift assist system.

Lift assessment

Activity: Handling of exhaust systems during manufacturing (05/09/2025)	Individuals/team involved: Andrew James	Time task takes place: Mon-Fri (24 hours / day)
Activity type: Handling of exhaust systems during manufacturing	Items being handled: Exhaust Systems	Assessor: Martin Ashe
Indications that task is high risk: Task has a history of manual handling incidents or lost time	Department: Manufacturing	Site: Tenneco Highpoint

Risk factor	Colour band	Score	Control measures
Eliminate the manual lifting in the task	N/A	N/A	Install vacuum lift assist system.
Load weight/frequency	AMBER	4	Install vacuum lift assist system.
Hand distance from lower back	AMBER	3	Install vacuum lift assist system.
Vertical lift zones	AMBER	1	Install vacuum lift assist system.
Torso twisting and sideways bending	AMBER	1	Install vacuum lift assist system.
Postural constraints	GREEN	0	Not asked
Grip on the load	AMBER	1	Install vacuum lift assist system.
Floor surface	GREEN	0	Not asked
Environmental factors	GREEN	0	N/A

8.2. MAC Carrying Assessment Report

Manual handling carry assessment for the P6 MHEV exhaust system, as discussed in Section 1.2, summarising key ergonomic risk factors and recommended control measures such as the installation of a vacuum lift assist system.

Carry assessment

Activity: Handling of exhaust systems within during manufacturing (05/09/2025)	Individuals/team involved: Andrew James	Time task takes place: Mon-Fri (24 hours / day)
Activity type: Handling of exhaust systems within during manufacturing	Items being handled: Exhaust Systems	Assessor: Martin Ashe
Indications that task is high risk: Task has a history of manual handling incidents or lost time	Site: Tenneco Highpoint	Department: Manufacturing

Risk factor	Colour band	Score	Control measures
Eliminate the manual lifting in the task	N/A	N/A	Install vacuum lift assist system.
Load weight/frequency	AMBER	4	Install vacuum lift assist system.
Hand distance from lower back	AMBER	3	Install vacuum lift assist system.
Asymmetrical torso or load	RED	2	Install vacuum lift assist system.
Postural constraints	GREEN	0	Not asked
Grip on the load	AMBER	1	Install vacuum lift assist system.
Floor surface	GREEN	0	Not asked
Carry distance	AMBER	1	Install vacuum lift assist system. Move stillage closer to leak test operation.
Obstacles on route	AMBER	2	Install vacuum lift assist system.
Environmental factors	GREEN	0	N/A

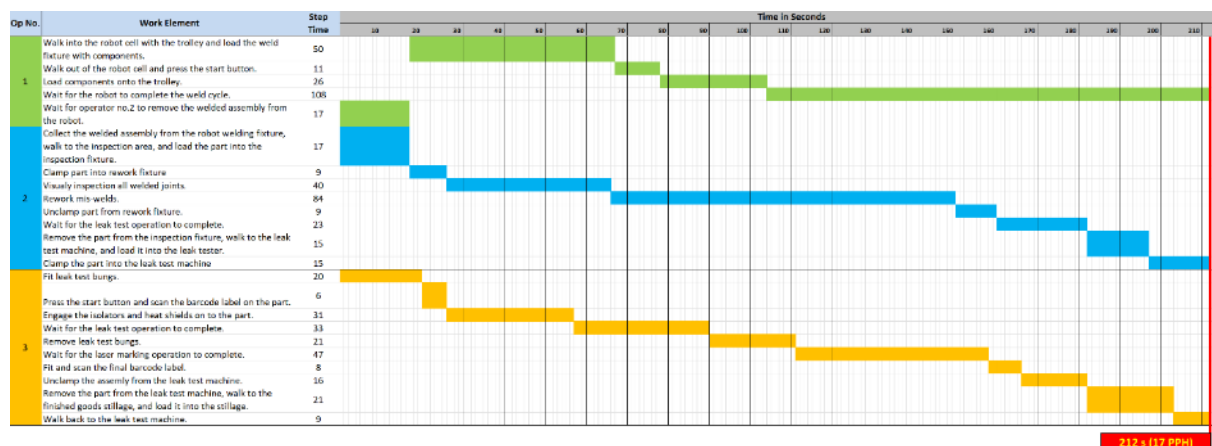
8.3. Robot 31 Time and Motion Study (1-man lift)

Time and motion study for each team member on Robot 31, as discussed in Section 1.2; this considers one team member handling the exhaust system.

TIME OBSERVATION SHEET															
Process:	Robot 31 - Operator No. 1 (Robot Loader)		Observer:				Martin Ashe				Date:	07/09/2025		Page:	1
Observation Documentation			Observed Times (secs)										Avg Time	Chosen Step Time	
Step#	Work Element	Remarks	1	2	3	4	5	6	7	8	9	10			
1	Walk into the robot cell with the trolley and load the weld fixture with components.	Includes scanning of 2 barcode labels on sub-components.	50	53	48	47	46	52	49	50	46	51	49.2	50	
2	Walk out of the robot cell and press the start button.	This energises the pneumatic clamps. The weld cycle does not start until the opposite station has finished welding.	12	12	10	13	9	10	12	11	11	10	11.0	11	
3	Load components onto the trolley.	The robot is welding in parallel with this step (robot welding cycle: 133 s).	27	29	25	26	24	26	25	27	25	25	25.9	26	
4	Wait for the robot to complete the weld cycle.	Once the previous weld cycle has completed, the station will rotate 180°.	106	104	108	107	109	107	108	106	108	108	107.1	108	
5	Wait for operator no.2 to remove the welded assembly from the robot.		18	16	17	15	16	16	15	17	16	16	16.2	17	
Total Time For 1 Cycle (secs)			213	214	208	208	204	211	209	211	206	210	209	212	
Parts Per Hour			16.9	16.8	17.3	17.3	17.6	17.1	17.2	17.1	17.5	17.1	17.2	17.0	

TIME OBSERVATION SHEET														
Process: Robot 31 - Operator No. 2 (Inspection & Rework Welder)			Observer: Martin Ashe			Date: 07/09/2025			Page: 1					
Observation Documentation			Observed Times (secs)										Avg Time	Chosen Step Time
Step#	Work Element	Remarks	1	2	3	4	5	6	7	8	9	10		
1	Collect the welded assembly from the robot welding fixture, walk to the inspection area, and load the part into the inspection fixture.		15	16	17	15	16	17	17	16	17	17	16.3	17
2	Clamp part into rework fixture		9	10	10	7	8	9	8	8	9	8	8.6	9
3	Visually inspection all welded joints.		38	40	37	39	40	41	38	39	40	40	39.2	40
4	Rework mis-welds.		83	75	80	94	86	75	86	90	76	86	83.1	84
5	Unclamp part from rework fixture.		9	9	7	8	8	9	8	9	7	8	8.2	9
6	Wait for the leak test operation to complete.		22	23	21	21	22	22	22	23	21	24	22.1	23
7	Remove the part from the inspection fixture, walk to the leak test machine, and load it into the leak tester.		14	15	15	13	14	14	14	15	15	13	14.2	15
8	Clamp the part into the leak test machine		15	15	13	13	15	14	15	14	14	15	14.3	15
Total Time For 1 Cycle (secs)			205	203	200	210	209	201	208	214	199	211	206	212
Parts Per Hour			17.6	17.7	18.0	17.1	17.2	17.9	17.3	16.8	18.1	17.1	17.5	17.0

TIME OBSERVATION SHEET														
Process:	Robot 31 - Operator No. 3 (Leak Test and Packing)				Observer:	Martin Ashe				Date:	07/09/2025		Page:	1
Observation Documentation				Observed Times (secs)								Avg Time	Chosen Step Time	
Step#	Work Element	Remarks	1	2	3	4	5	6	7	8	9			10
1	Fit leak test bungs.		19	20	20	18	17	19	21	20	20	19	19.3	20
2	Press the start button and scan the barcode label on the part.	This initiates the leak test operation.	6	6	6	5	5	5	6	5	5	5	5.4	6
3	Engage the isolators and heat shields on to the part.	The leak test operation starts in parallel with this step (leak test cycle: 63 s).	34	31	29	30	30	33	31	28	29	31	30.6	31
4	Wait for the leak test operation to complete.		29	32	34	33	33	30	32	35	34	32	32.4	33
5	Remove leak test bungs.	The laser marking operation starts in parallel with this step (laser marking cycle: 67 s).	19	19	22	20	22	22	20	19	21	20	20.4	21
6	Wait for the laser marking operation to complete.		48	48	45	47	45	45	47	48	46	47	46.6	47
7	Fit and scan the final barcode label.	This disengages the locks on the clamps.	6	8	8	8	7	8	6	6	7	8	7.2	8
8	Unclamp the assembly from the leak test machine.		15	16	15	14	17	15	15	14	16	15	15.2	16
9	Remove the part from the leak test machine, walk to the finished goods stillage, and load it into the stillage.		22	21	19	19	21	22	23	20	20	21	20.8	21
10	Walk back to the leak test machine.		8	9	8	9	9	8	8	7	8	8	8.2	9
Total Time For 1 Cycle (secs)			206	210	206	203	206	207	209	202	206	206	206	212
Parts Per Hour			17.5	17.1	17.5	17.7	17.5	17.4	17.2	17.8	17.5	17.5	17.5	17.0



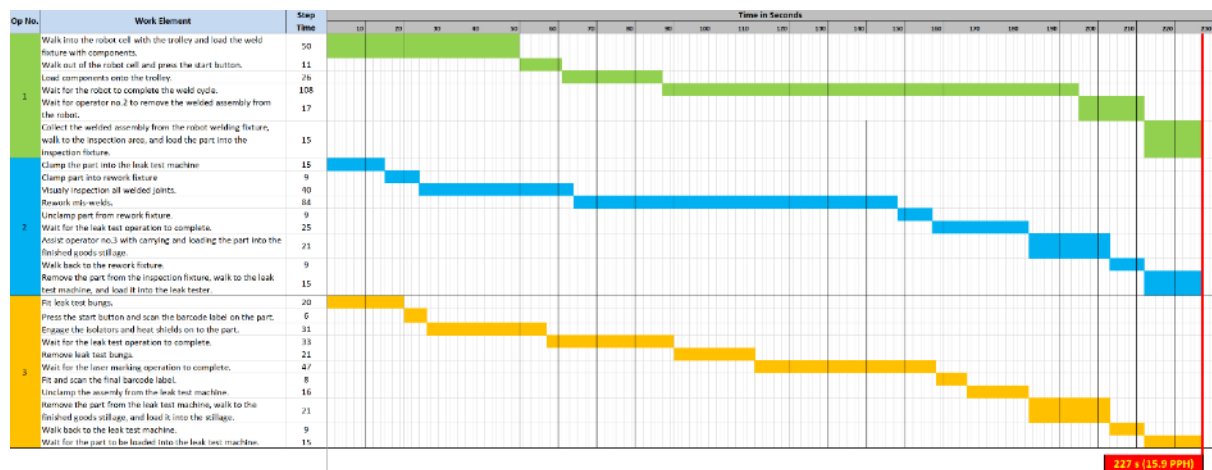
8.4. Robot 31 Time and Motion Study (2-man lift)

Time and motion study for each team member on Robot 31, as discussed in Section 1.2; this considers two team members handling the exhaust system.

TIME OBSERVATION SHEET															
Process:	Robot 31 - Operator No. 1 (Robot Loader)		Observer:			Martin Ashe				Date:		21/10/2025		Page:	1
Observation Documentation			Observed Times (secs)										Avg Time	Chosen Step Time	
Step#	Work Element	Remarks	1	2	3	4	5	6	7	8	9	10			
1	Walk into the robot cell with the trolley and load the weld fixture with components.	Includes scanning of 2 barcode labels on sub-components.	50	53	48	47	46	52	49	50	46	51	49.2	50	
2	Walk out of the robot cell and press the start button.	This energises the pneumatic clamps. The weld cycle does not start until the opposite station has finished welding.	12	12	10	13	9	10	12	11	11	10	11.0	11	
3	Load components onto the trolley.	The robot is welding in parallel with this step (robot welding cycle: 133 s).	27	29	25	26	24	26	25	27	25	25	25.9	26	
4	Wait for the robot to complete the weld cycle.	Once the previous weld cycle has completed, the station will rotate 180°.	106	104	108	107	109	107	108	106	108	108	107.1	108	
5	Wait for operator no.2 to remove the welded assembly from the robot.		18	16	17	15	16	16	15	17	16	16	16.2	17	
6	Collect the welded assembly from the robot welding fixture, walk to the inspection area, and load the part into the inspection fixture.		14	13	15	14	14	13	16	14	15	15	14.3	15	
Total Time For 1 Cycle (secs)			227	227	223	222	218	224	225	225	221	225	224	227	
Parts Per Hour			15.9	15.9	16.1	16.2	16.5	16.1	16.0	16.0	16.3	16.0	16.1	15.9	

TIME OBSERVATION SHEET																
Process:	Robot 31 - Operator No. 2 (Inspection & Rework Welder)					Observer:			Martin Ashe			Date:	21/10/2025		Page:	1
Observation Documentation					Observed Times (secs)								Avg Time	Chosen Step Time		
Step#	Work Element		Remarks		1	2	3	4	5	6	7	8			9	10
1	Clamp the part into the leak test machine				15	15	13	13	15	14	15	14	14	15	14.3	15
2	Clamp part into rework fixture				9	10	10	7	8	9	8	8	9	8	8.6	9
3	Visually inspection all welded joints.				38	40	37	39	40	41	38	39	40	40	39.2	40
4	Rework mis-welds.				83	75	80	94	86	75	86	90	76	86	83.1	84
5	Unclamp part from rework fixture.				9	9	7	8	8	9	8	9	7	8	8.2	9
6	Wait for the leak test operation to complete.				24	25	23	23	24	24	24	25	23	26	24.1	25
7	Assist operator no.3 with carrying and loading the part into the finished goods stillage.				22	21	19	19	21	22	23	20	20	21	20.8	21
8	Walk back to the rework fixture.				7	8	8	9	8	9	9	8	9	9	8.4	9
9	Remove the part from the inspection fixture, walk to the leak test machine, and load it into the leak tester.				14	15	15	13	14	14	14	15	15	13	14.2	15
Total Time For 1 Cycle (secs)					221	218	212	225	224	217	225	228	213	226	221	227
Parts Per Hour					16.3	16.5	17.0	16.0	16.1	16.6	16.0	15.8	16.9	15.9	16.3	15.9

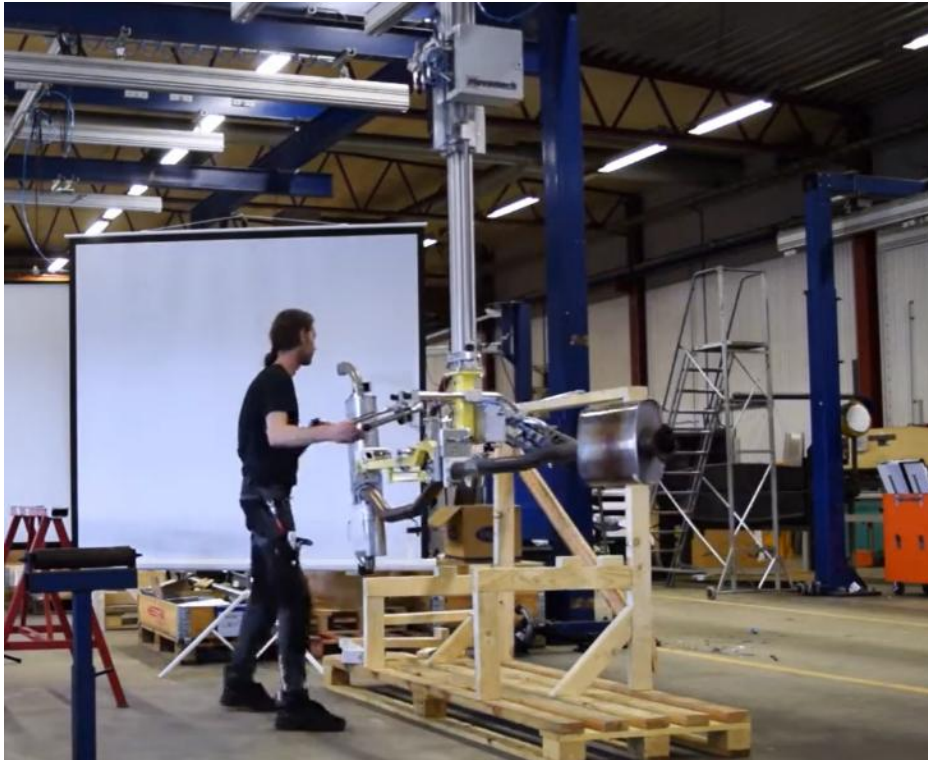
TIME OBSERVATION SHEET														
Process: Robot 31 - Operator No. 3 (Leak Test and Packing)			Observer: Martin Ashe				Date: 21/10/2025				Page: 1			
Observation Documentation			Observed Times (secs)										Avg Time	Chosen Step Time
Step#	Work Element	Remarks	1	2	3	4	5	6	7	8	9	10		
1	Fit leak test bungs.		19	20	20	18	17	19	21	20	20	19	19.3	20
2	Press the start button and scan the barcode label on the part.	This initiates the leak test operation.	6	6	6	5	5	5	6	5	5	5	5.4	6
3	Engage the isolators and heat shields on to the part.	The leak test operation starts in parallel with this step (leak test cycle: 63 s).	34	31	29	30	30	33	31	28	29	31	30.6	31
4	Wait for the leak test operation to complete.		29	32	34	33	33	30	32	35	34	32	32.4	33
5	Remove leak test bungs.	The laser marking operation starts in parallel with this step (laser marking cycle: 67 s).	19	19	22	20	22	22	20	19	21	20	20.4	21
6	Wait for the laser marking operation to complete.		48	48	45	47	45	45	47	48	46	47	46.6	47
7	Fit and scan the final barcode label.	This disengages the locks on the clamps.	6	8	8	8	7	8	6	6	7	8	7.2	8
8	Unclamp the assembly from the leak test machine.		15	16	15	14	17	15	15	14	16	15	15.2	16
9	Remove the part from the leak test machine, walk to the finished goods stillage, and load it into the stillage.		22	21	19	19	21	22	23	20	20	21	20.8	21
10	Walk back to the leak test machine.		8	9	8	9	9	8	8	7	8	8	8.2	9
11	Wait for the part to be loaded into the leak test machine.		14	15	15	13	14	14	14	15	15	13	14.2	15
Total Time For 1 Cycle (secs)			220	225	221	216	220	221	223	217	221	219	220	227
Parts Per Hour			16.4	16.0	16.3	16.7	16.4	16.3	16.1	16.6	16.3	16.4	16.3	15.9



8.5. Exhaust Handling Device Images

The following images illustrate the exhaust system handling devices discussed in the Section 2.2.3.

Appendix 8.5.1 – Movomech Exhaust Lift Assist



Appendix 8.5.2 – Givens Engineering Exhaust Lift Assist



Appendix 8.5.3 – PowerBuilt Exhaust Lift Assist



Appendix 8.5.4 – Knight Global Exhaust Lift Assist



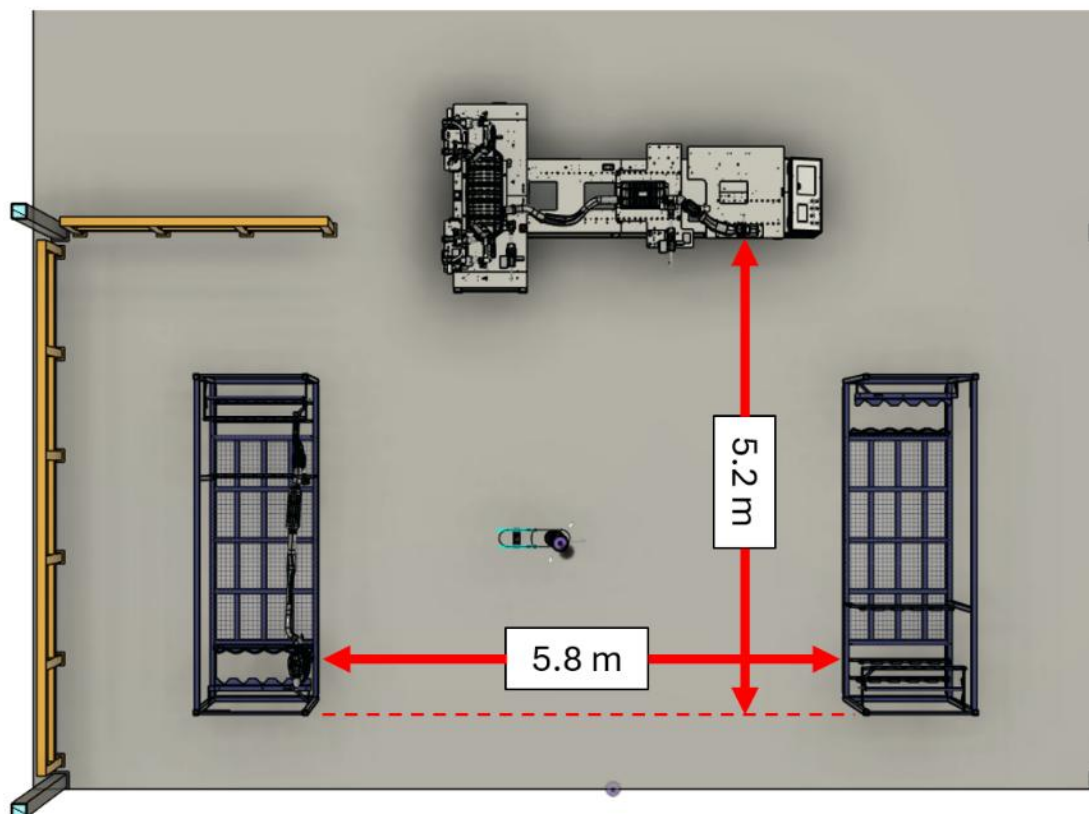
Appendix 8.5.5 – Tawi Exhaust Lift Assist (Tenneco Highpoint)



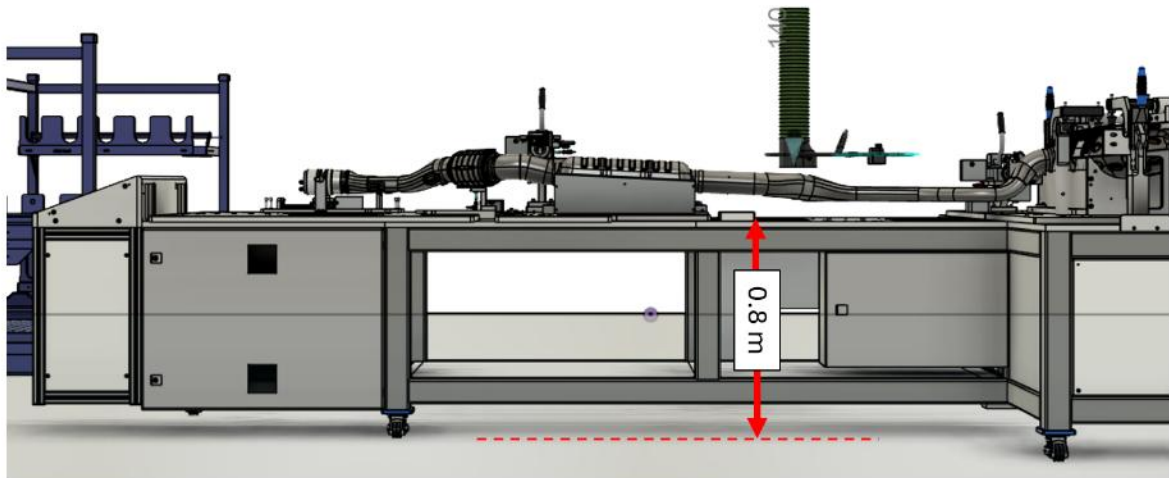
8.6. Robot 31 Equipment Layout Images

The following images illustrate Robot 31's cell layout, as discussed in the Section 2.2.4.

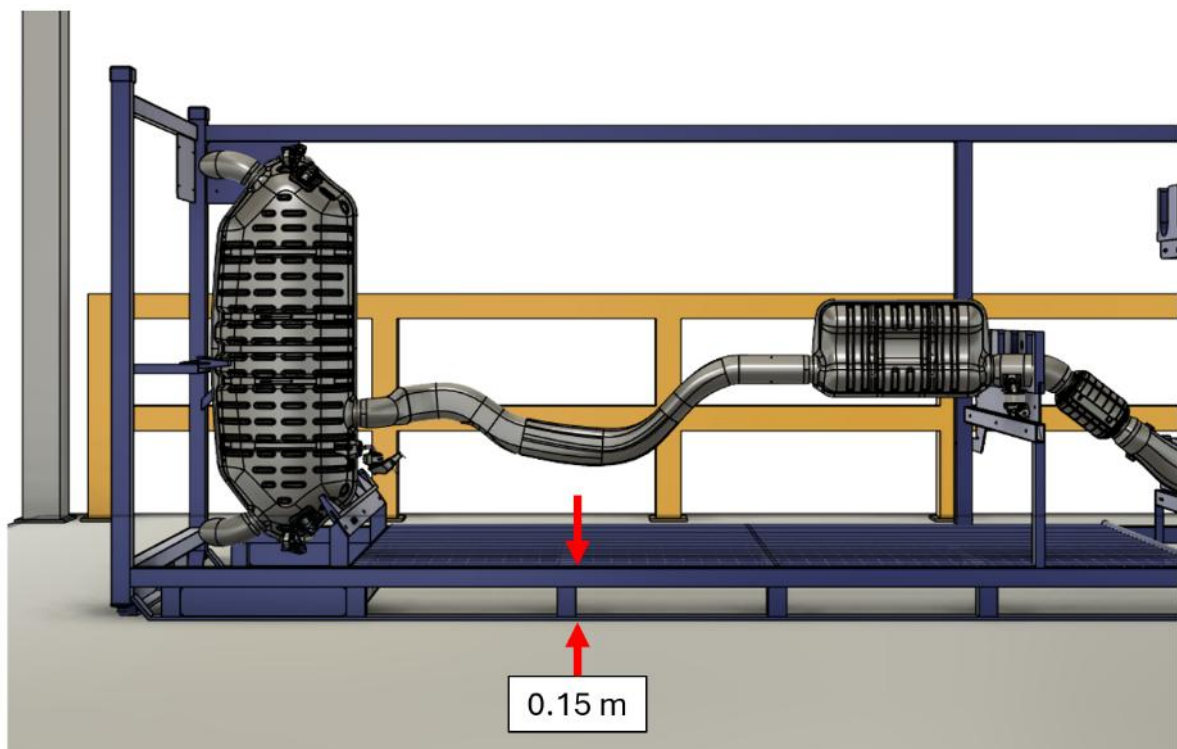
Appendix 6.1 – Robot 31 Plan View and Dimensions



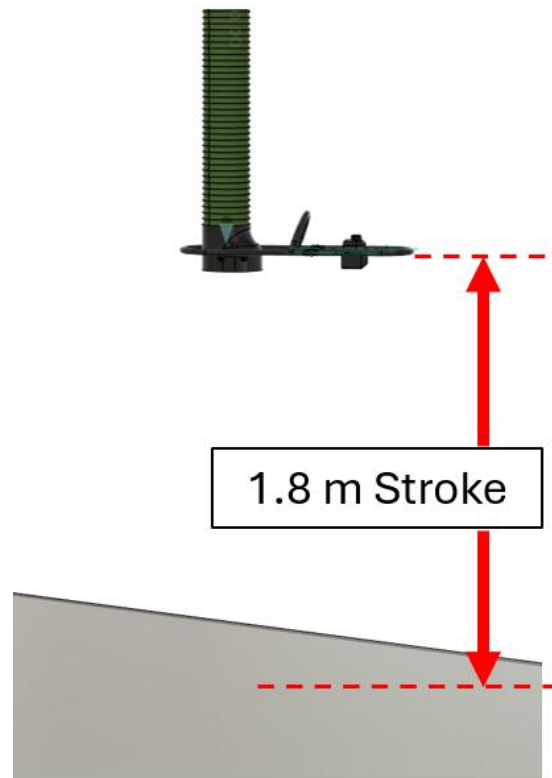
Appendix 6.2 – Leak Test Machine Bed Height



Appendix 6.3 – Stillage Base Height



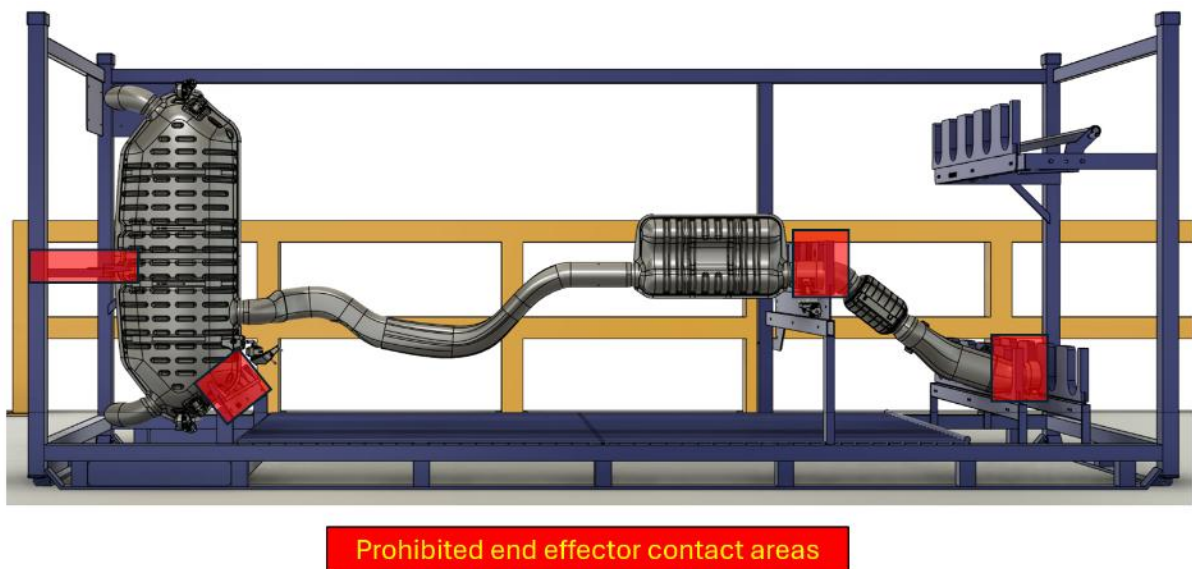
Appendix 6.4 – Vacuum Lift Tube Stroke



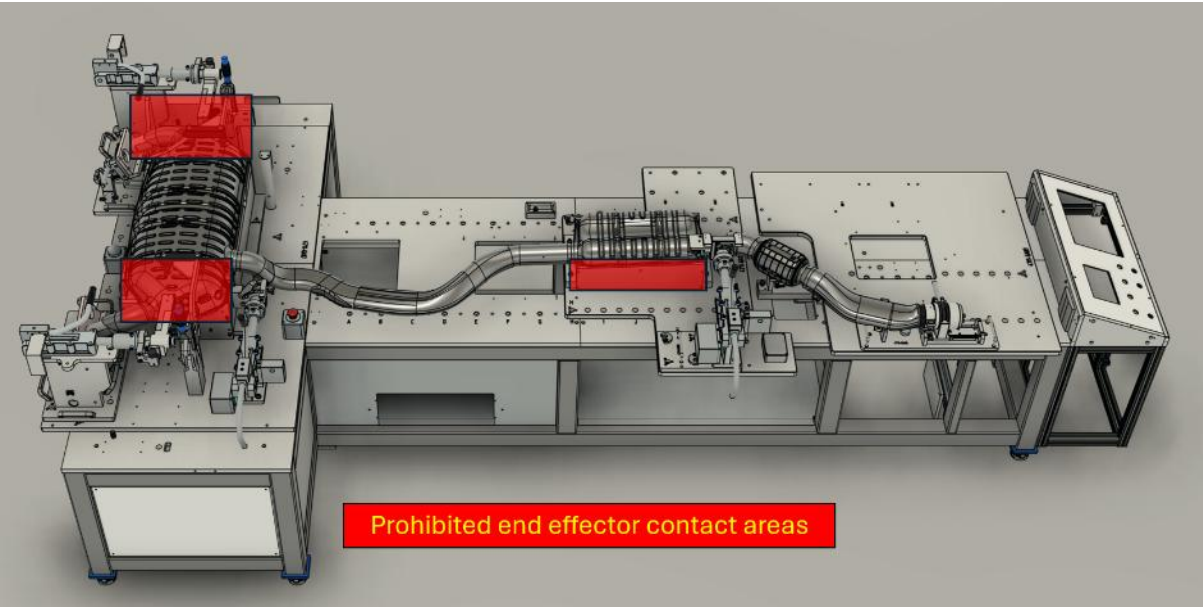
8.7. Prohibited End Effector Contact Areas

The following images illustrate the end effector interfacing constraints governed by the equipment, as discussed in the Section 2.2.4.

Appendix 7.1 – Stillage Interface Constraints

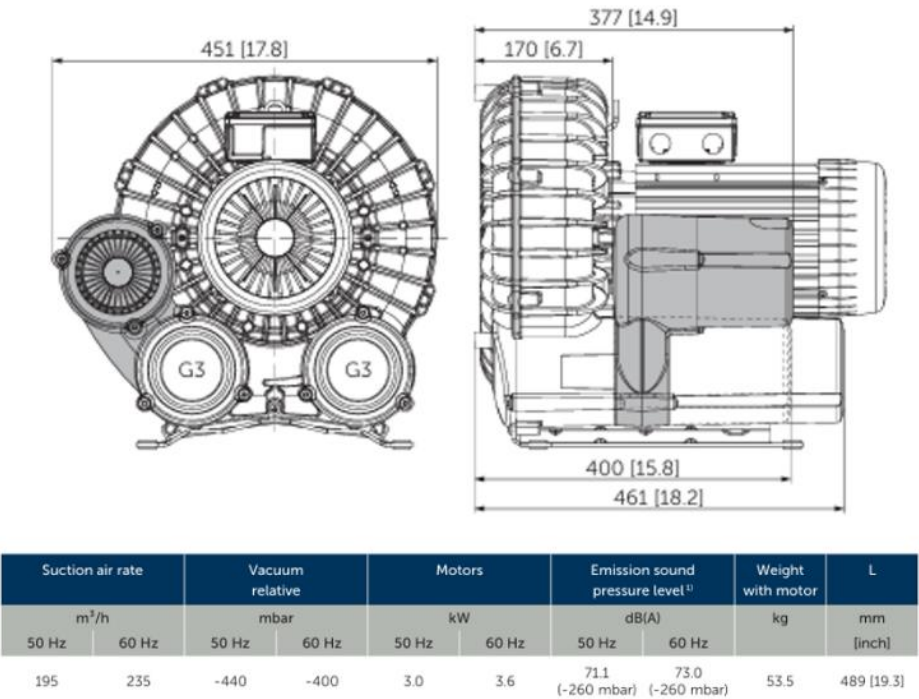


Appendix 7.2 – Leak Tester Interface Constraints



8.8. **Becker Vacuum Pump Specifications**

The image below contains the specification of the vacuum pump that is discussed in the Section 2.2.4.



8.9. British adult dimensions up to 65 years old

The table below contains the anthropometric data for British adults aged 19 to 65, which is discussed in Section 2.4.2.

DIMENSIONS	Men				Women			
	5th %ile	50th %ile	95th %ile	SD	5th %ile	50th %ile	95th %ile	SD
STANDING								
1 Stature	1640	1760	1880	73	1520	1620	1720	61
2 Eye height	1530	1650	1770	72	1415	1515	1615	60
3 Shoulder height	1330	1445	1555	69	1225	1320	1410	57
4 Elbow height	1020	1105	1195	54	940	1015	1090	45
5 Hip height	850	935	1020	52	745	815	885	43
6 Knuckle height	695	765	835	42	665	725	785	35
7 Fingertip height	595	665	730	40	565	630	690	38
SITTING								
8 Sitting height	855	915	980	37	800	855	915	35
9 Sitting eye height	740	795	855	36	690	745	800	33
10 Sitting shoulder height	545	600	655	33	510	560	610	31
11 Sitting elbow height	195	245	300	32	180	230	275	28
12 Thigh – thickness	130	160	185	16	120	150	175	16
13 Thigh – outer length	545	595	650	32	520	565	615	29
14 Thigh – inner length	445	500	555	34	430	475	525	29
15 Knee height	495	550	605	33	460	500	545	26
16 Under thigh height	400	445	495	30	355	400	445	27
17 Shoulder breadth a)	415	465	510	29	355	395	435	24
18 Shoulder breadth b)	370	405	440	21	330	360	390	18
19 Hip width	300	350	400	31	300	350	400	29
20 Chest depth	185	225	270	26	190	235	275	26
21 Abdominal depth	195	240	280	26	185	220	260	22
22 Elbow – shoulder length	335	370	405	21	305	330	360	17
23 Elbow – fingertip length	445	480	515	22	400	430	465	19
24 Arm – shoulder to fingertip	730	790	850	37	660	710	760	32
25 Arm – shoulder to grip	615	670	730	34	560	605	650	29
APPENDAGES								
26 Head length	185	195	210	8	170	180	190	7
27 Head breadth	145	155	165	7	135	145	155	5
28 Hand length	175	190	210	10	160	175	190	9
29 Hand breadth	80	90	95	5	70	75	85	4
30 Foot length	245	270	290	15	220	240	260	12
31 Foot breadth	90	100	110	7	80	90	100	5
REACH								
32 Span	1670	1815	1955	86	1500	1615	1730	70
33 Elbow span	875	955	1035	49	785	855	925	42
34 Vertical grip reach – standing	1950	2085	2220	83	1805	1915	2030	70
35 Vertical grip reach – sitting	1155	1260	1360	63	1070	1155	1245	52
36 Forward grip reach	730	790	845	36	655	705	755	31

8.10. Operator Requirements Survey – Vacuum Lift Assist Systems

The following surveys were completed by team members at Tenneco Highpoint and aided in defining the customer requirements (Section 3.2.2).

Operator Requirements Survey – Vacuum Lift Assist Systems

Project: Vacuum Lift Assist End Effector Development (Robot 31 VL 3).

Purpose: To gather operator feedback on current handling equipment and identify key requirements for an improved vacuum lift assist system.

Instructions: Please answer the questions based on your experience with the current exhaust-handling process in your area. Responses will support the development of a new and improved lift-assist unit for transferring L460/1 P6 MHEV exhaust assemblies between the leak-test machine and the finished-goods stillage on Robot 31.

Section 1 – Team Member Background

1. **Job role:**

- ☐ Production Operator
- ☒ Section Support Leader (SSL)
- ☐ Team Leader / Supervisor
- ☐ Other: _____

2. **Years of experience in this role:**

- ☐ < 1 year
- ☒ 1–3 years
- ☐ 3–5 years
- ☐ > 5 years

3. **How often do you handle exhaust systems per shift?**

- ☐ Occasionally (1–20 times)
- ☐ Regularly (20 - 60 times)
- ☒ Frequently (>60 times)

4. **What product do you handle? (e.g. L460/1 P6 PHEV Mid Assembly)**

P6 L461 / P6 L460 SWB + LWB

Section 2 – Current Handling Method

4. **How would you rate the physical effort required to handle the exhaust system using the current device?**

- ☐ Very low
- ☐ Low
- ☒ Moderate
- ☐ High
- ☐ Very high

5. Which body areas experience the most strain during the task? (Select all that apply)

- ☒ Lower back
☐ Shoulders
☐ Wrists/hands
☐ Neck
☒ Legs
☐ None

6. Have you experienced discomfort or fatigue after performing this task?

- ☐ Never
☒ Occasionally
☐ Frequently

7. If you have experienced discomfort or fatigue, what were your symptoms?

Pain in the side & back

Section 3 – Requirements for the Vacuum Lift Assist

For each requirement, please rate its importance.

Scale: 1 = Not important, 5 = Very important

7. The system should significantly reduce manual lifting effort.

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☒

8. The control handle should be positioned at a comfortable height for different operators.

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☒

9. The system should allow smooth movement in the X-Y plane with minimal resistance.

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☒

10. The exhaust should be easily rotated between horizontal and vertical orientations.

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☒ N/A ☐

11. The system should feel safe and stable when holding, transporting, and unloading the exhaust.

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☒

Section 4 – Safety and Usability

12. How important is clear feedback that the exhaust is securely held (e.g. sound, feel, indicator)?

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☒

13. How easy should the system be to learn to use?

- ☐ Very easy (no training required)
☒ Easy (short instruction)
☐ Moderate (formal training required)

Section 5 – Open Feedback

14. What is the biggest problem with the current exhaust handling method?

The moving of parts in different planes – bearings should be/feel easier to move.

15. Are there any features you would like to see in a new lift assist system?

Should be a light weight system
 Easy to move - no resistance
 Air gauge / suction gauge.
 Controlled movement - horizontal to vertical

Thank you for your input. Your feedback is essential to improving safety, ergonomics, and productivity.

8.11. Assessment of Competitor Exhaust Handling Devices

The following table presents the benchmarking results for competitor exhaust handling devices, evaluated against the customer requirements detailed in Section 3.2.4.

Customer Requirement	Competitors				
	Movomech	Givens Engineering	PowerBuilt	Knight Global	Tawi
Zero red-category handling risks	5	4	4	4	3
Interfaces with existing lift control handle	N/A	N/A	N/A	N/A	N/A
Easily pivots between the horizontal and vertical planes	5	1	1	5	1
Operable by a single team member	5	5	5	5	5
Cycle time is maintained <= 212 s	3	4	3	4	4
Materials/structure can meet production lifetime volumes	4	3	4	2	4
System is easy to inspect	4	4	4	3	4
System is easy to maintain	3	4	3	3	4
System can operate 12 months without requiring thorough maintenance examination	4	3	4	3	4
Cost is kept within budget	2	5	3	2	5
The lift assist system provides a safe margin against structural overload	5	3	4	3	3
Load remains securely attached during lifting and positioning	5	4	5	4	4
System provides real-time vacuum level feedback to the operator	N/A	N/A	N/A	N/A	1
Working height is adjustable to accommodate the 5th percentile female to the 95th percentile male	5	4	4	4	4
Design minimises excessive trunk flexion and torsion loading	4	3	4	4	3
Low manual effort to manipulate device	5	4	5	4	3
System fails in a safe manner in the event of vacuum loss or power failure	N/A	N/A	N/A	N/A	3
System does not interfere with surrounding equipment or restricted zones	3	4	1	4	5

8.12. End-effector DFMEA

The following table presents the results of a Design Failure Modes & Effects Analysis that was conducted for the end-effector design (Section 3.3).

Item	Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Class	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Design Prevention Controls	Current Design Detection Controls	Detect	RPN	AP	Recommended Action(s)	Responsibility and Target Completion Date	Action Results				
															Severity	Occur	Detect	RPN	AP
Vacuum suction cup(s)	Securely grip the exhaust system using vacuum suction cups	Loss of grip during pick-up or travel (cup(s) release from surface) Insufficient initial seal at pick-up (cannot achieve target vacuum to lift) Uneven/partial gripping (only subset of cups sealed, unstable load)	Dropped part: - Injury risk - Damage to exhaust, stillage, or leak tester - Production downtime	9	Safety	Damaged/aged vacuum cup	3	Incoming inspection spec for cup Shore hardness	Pre use inspection checklist Defined replacement interval in maintenance plan	4	108	L							
						Leaks in hoses/fittings	3	Vacuum gauge with green/amber/red zones	Pre use inspection checklist Pressure hold test after assembly (e.g., 30 s hold, ≤ XkPa drop)	4	108	L							
						Vacuum cups placed in the wrong location (prohibited surface)	3	Defined permitted contact zones	Cup placement verification during design review using CAD interference study	2	54	L							
						Missing/incorrect vacuum gauge feedback	3	Vacuum gauge according to DIN EN 837-1 Visual inspection of vacuum line installation	4	108	L								
	Interface safely with exhaust system at permitted contact points	Grips on prohibited areas (e.g., inlet pipe). Cup footprint clashes with fixtures (stillage/leak tester), preventing correct seating.	Exhaust damage (coupling/pipe, cosmetic dents) Vacuum cup damage	6	Soft	Inadequate cup spacing for variant geometry	2	Implement variant tolerant rail/slide	Validate during physical trials with production operatives and engineers	2	24	L							
						Operator visibility/markings poor	4	Incorporate visual cues for cup placement	Validate during physical trials with production operatives and engineers	2	48	L							
						No alignment locator or template	2	Incorporate hard stops/locators for cup placement	Validate during physical trials with production operatives and engineers	2	24	L							
Vacuum hoses and suction cup(s)	Maintain vacuum hold during lifting and movement	Vacuum decays below safe threshold during transfer Sudden vacuum loss (line disconnect/valve open → immediate release)	- Uncontrolled release/swing - High severity injury - Damage to exhaust - Production downtime	9	Safety	End effector mass too high	2	Maximum end effector mass ≤ 18 kg. Check using CAD mass properties.	Physical mass verification after manufacture	2	36	L							
						Mis-set control valve	3	Vacuum gauge with green/amber/red zones to aid setting	Safe Working Load testing during commissioning and 12-month inspection	3	81	L							
						Blocked vacuum lines	3	Vacuum gauge with green/amber/red zones	12-month inspection	4	108	L							
Pivot Coupling	Pivot/rotate the exhaust from horizontal to vertical	Uncontrolled rotation (overshoot/swing). Rotation torque exceeds ergonomic limit → operator cannot complete rotate smoothly. Locking/positioning feature fails (if used).	- Misalignment / collision with stillage/leak tester - Operator strain - Increased cycle time	7	Soft	CoG not aligned with rotation axis	4	CoG study from CAD	CoG validation test with physical prototype	4	112	M							
						Friction/wear in pivot	5	Pivot mechanism rated for 800,000 cycles	Axial/radial play check with feeler gauge/indicator and a wear limit	4	140	M							
						Handle placement outside reach envelope	2	Design using anthropometric handle height window and ISO 11226 posture limits	Physical verification to ensure handle positions conform to anthropometric handle height window and ISO 11226 posture limits	2	28	L							
						Insufficient damping/gear ratio	6	None	Measure maximum acceleration using smartphone attached to end effector	5	210	H	Mechanical damping to be designed into pivot to limit angular acceleration (%/s²)	M Ashe - 05/03/26	7	3	5	105	M
Main end-effector framework	Support and distribute load through structural frame	Structural yielding/bending under rated load. Fatigue/weld crack at high stress joints. Fastener loosening → geometry shift.	- Misalignment of grippers - Catastrophic failure → dropped load	9	Hard	Under sized wall thickness	3	Maximum stress (σ) in fatigue-critical structural members ≤ 0.6 × σ _{yield} under worst-case load (FEA) Maximum deflection between interfaces ≤ 10 mm (FEA)	Safe Working Load (deflection) testing during commissioning and 12-month inspection	3	81	L							
						Poor weld joint geometry	4	None	Visual inspection of external weld quality	6	216	H	Weld design standards as per ISO 2553 Prototype / sample weld sectioning & macro-etch validation	M Ashe - 05/03/26	9	3	3	81	L
						Inadequate FoS	3	Static FoS under maximum rated load condition ≥ 2	Safe Working Load (deflection) testing during commissioning and 12-month inspection	4	108	L							
						Inadequate torque spec for joints	6	None	Torque measurement verification during physical sign-off and 12-month inspection	4	216	H	Fastener torque derived using VDI 2230 joint analysis	M Ashe - 05/03/26	9	3	4	108	L

8.13. Product Design Specification Table

The following table contains a list of the end-effector design requirements that are discussed in Section 3.4.

Category	Requirement
1.0 Performance	1.1 Pivot at least 90° from vertical to horizontal plane
	1.2 Cycle time to transfer exhaust between the leak tester and stillage must not exceed 21 s.
	1.3 Minimum vacuum during operation: -35 kPa
	1.4 Max stress $\sigma_{max} \leq 0.6 \times \sigma_{yield}$ under worst-case load
	1.5 Maximum deflection between exhaust interfaces: 10 mm
	1.6 End-effector shall accommodate the geometry of all exhaust variants.
	1.7 The exhaust system angular deviation in the horizontal plane shall not exceed 15° during lifting and transfer operations.
	1.8 Fastener preload shall be derived using VDI 2230 joint analysis.
2.0 Environment	2.1 The product must operate sufficiently between 15 and 25 °C.
	2.2 Indoor industrial environment (no outdoor exposure).
	2.3 No corrosive atmosphere.
3.0 Life in Service	3.1 The product must withstand a minimum of 400k operating cycles.
	3.2 The fatigue-critical pivot mechanism must withstand a minimum of 800k operating cycles.
4.0 Target Costs	4.1 Manufacturing costs must not exceed £20k.
5.0 Volume/Demand	5.1 One unit required.
6.0 Maintenance	6.1 Pre-use inspection time limit: 4 mins
	6.2 Preventative Maintenance time limit: 60 mins
	6.3 Minimum maintenance interval: 12 months
7.0 Physical Restrictions (Size & Weight)	7.1 Connects with vacuum control handle via two 9 mm Ø mm holes spaced 120 mm apart.
	7.2 Prohibited exhaust contact areas must be respected.
	7.3 Weight must not exceed 18 Kg.
	7.4 Minimum vacuum suction cup area: 631 cm².
	7.5 Maximum end-effector width: 2000 mm
	7.6 Maximum end-effector length: 800 mm
8.0 Manufacturing Processes	8.1 Weld design standards as per ISO 2553.
	8.2 Fasteners shall be tightened to the analytically derived torque value ($\pm X\%$) using calibrated torque tools.
9.0 Ergonomics	9.1 No residual HSE risks shall be classified as "High" following risk assessment.
	9.2 Operable by a single team member
	9.3 Maximum of 2 control interfaces (handles).
	9.4 Working height range: 965 - 1220 mm
	9.5 Maximum shoulder flexion angle during operation: 90°
	9.6 Maximum trunk torsion angle range during operation: -20 - 20°
	9.7 Maximum trunk flexion angle during operation: 60°
	9.8 Maximum initial excitation force: 100 N
	9.9 Maximum sustained excitation force: 70 N
10.0 Safety	10.1 The product must not have any sharp edges or burrs.
	10.2 SWL to be labelled on equipment.
	10.3 Vacuum gauge to be positioned within view of the operator.
	10.4 Green/Amber/Red zones on vacuum gauge.
	10.5 Vacuum gauge according to DIN EN 837-1.
	10.5 Exhaust remains attached to end-effector
	10.6 Minimum static FOS under maximum rated load condition: 2
	10.7 Incorporates hard stops/locators for vacuum cup placement.
	10.8 The pivot mechanism shall incorporate mechanical damping to limit angular acceleration during operation. The maximum allowable angular acceleration ($^{\circ}/s^2$) shall be established during Product Validation (PV) testing, based on safe and stable handling criteria under maximum-rated load conditions.
11.0 Testing (Design Verification & Product Validation)	11.1 Vacuum pressure leakage test (e.g., 30 s hold, $\leq X$ kPa drop)
	11.2 Safe Working Load deflection testing to be completed prior to sign-off.
	11.3 CAD CoG study to verify equilibrium angle does not exceed 15°.
	11.4 A full requirement verification matrix shall be completed to demonstrate compliance with all PDS specifications prior to product sign-off.
	11.5 Validate maximum acceleration using smartphone attached to end-effector.
	11.6 Weld joint integrity to be verified through macro-etch examination of representative weld samples to confirm penetration and throat adequacy.
12.0 Documentation	12.1 Preventative Maintenance Plan to be created and implemented.
	12.2 Operational instructions to be created.
	12.3 Pre-use inspection checklist to be created.
13.0 Training	13.1 Operators must be provided adequate training.

8.14. Concept Screening Decision Matrices

These decision matrices were used to assess the functional design concepts discussed in Section 4.2.

Appendix 8.14.1 - Rear Gripping Method Decision Matrix

Criteria	Weighting	Rear Gripping Method Concepts		
		Dual silicone vacuum cups	Dual metal vacuum cups with geranium interface	Single metal vacuum cup with geranium interface
Gripping Reliability	0.40	1.2	2	1.2
Durability and Maintainability	0.25	0.5	1	1
Manufacturing Cost and Complexity	0.20	1	0.6	0.8
Weight	0.15	0.75	0.6	0.6
Total Weighted Ratings		3.45	4.2	3.6

Appendix 8.14.2 - Front Gripping Method Decision Matrix

Criteria	Weighting	Front Gripping Method Concepts		
		Pneumatic gripper cylinder	Silicone resonator vacuum cup	Cradle-type saddle
Gripping Reliability	0.40	1.6	1.2	1.6
Durability and Maintainability	0.25	1	0.75	1.25
Manufacturing Cost and Complexity	0.20	0.4	0.6	1
Weight	0.15	0.45	0.6	0.45
Total Weighted Ratings		3.45	3.15	4.3

Appendix 8.14.3 – Pivot Mechanism Decision Matrix

Criteria	Weighting	Pivot Mechanism Concepts		
		Cartridge bearing pivot with manual rotation and remote-activated locking pin	Single pivot with cartridge bearings. Rotated via pneumatic cylinder with push button	Single pivot pin joint with a greased bush. Manually rotated. Mechanical locking pin with hand lever actuation
Ease of Operation	0.35	1.4	1.75	1.4
Motion Control and Stability	0.30	1.2	1.2	1.2
Durability and Maintainability	0.20	1	0.6	0.8
Manufacturing Cost and Complexity	0.15	0.75	0.3	0.6
Total Weighted Ratings		4.35	3.85	4

Appendix 8.14.4 – Pivot Damping Decision Matrix

Criteria	Weighting	Pivot Damping Concepts		
		Friction washer stack	Rotary viscous damper	Gas strut damper
Motion Control and Stability	0.40	1.2	2	2
Durability and Maintainability	0.25	0.5	1	1
Packaging and Integration	0.20	0.8	0.8	0.6
Manufacturing Cost and Complexity	0.15	0.75	0.6	0.45
Total Weighted Ratings		3.25	4.4	4.05

Appendix 8.14.5 – Variant Accommodation Decision Matrix

Criteria	Weighting	Variant Accommodation Concepts		
		Fixed geometry design	Sliding control assembly for longitudinal adjustment	Sliding ballast weight
Stability	0.45	0.9	2.25	2.25
Ease of Adjustment	0.20	1	0.6	0.8
Packaging and Integration	0.20	1	0.8	0.6
Manufacturing Cost and Complexity	0.15	0.75	0.45	0.6
Total Weighted Ratings		3.65	4.1	4.25

Appendix 8.14.6 – Structural Frame Decision Matrix

Criteria	Weighting	Structural Frame Concepts		
		Welded steel box section	Aluminium extrusion with bolted joints	Tubular steel with bolted joints
Strength and Rigidity	0.40	2	1.6	1.6
Weight	0.25	1	1.25	0.75
Durability	0.20	1	0.8	0.8
Manufacturing Cost and Complexity	0.15	0.6	0.6	0.45
Total Weighted Ratings		4.6	4.25	3.6

Appendix 8.14.7 – Location Guides Decision Matrix

Criteria	Weighting	Location Guides Concepts		
		Fixed bars that align with the edges of the rear muffler and resonator	Tapered saddle that interfaces with the muffler inlet pipe and/or the resonator outlet pipe	Integrate alignment features into the rear muffler suction cup(s)
Locating Effectiveness	0.40	1.2	2	1.6
Ease of Operation	0.30	0.9	1.2	1.2
Durability	0.20	1	1	1
Manufacturing Cost and Complexity	0.10	0.5	0.4	0.4
Total Weighted Ratings		3.6	4.6	4.2

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