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Strathclyde
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**Integrating Robotic Welding Constraints into the Structural
Optimisation of Ship Structures for Enhanced Automated
Production**

By:

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Author statement

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Abstract

The maritime industry faces significant challenges in automating the assembly of complex ship structures. While automated joining is successfully implemented in open-block stages using inverted welding gantries, automation is severely obstructed once structures are assembled into enclosed, closed-block configurations. The ship's double bottom represents a critical application of these confined environments, requiring robotic systems to navigate internally within tight compartments. Conventional structural optimisation historically prioritised weight minimisation, introducing complex, dense stiffener layouts that render closed geometries "manufacture-impenetrable" and kinematically inaccessible to industrial robots. To bridge this gap, this thesis proposes a novel framework that embeds robotic welding constraints directly into the early-stage structural design phase as active, multi-objective parameters.

Executed through a five-phase methodology, this research first maps industrial gaps via a systematic review, establishing the baseline for "Design for Automation." Second, production simulation of the double-bottom structural geometry demonstrates that robotic welding achieves an estimated 3.85-fold speed increase and a 1:2.75 energy-to-labour cost ratio over manual methods. Third, a structural optimisation engine coupling a Multi-Objective Genetic Algorithm with Response Surface Methodology is formulated to concurrently minimise mass and weld lengths. Fourth, a high-fidelity Virtual Prototyping Framework isolates kinematic limits within a

compressed 1.2-meter clearance, proving the Elevated (On-Stiffener) configuration as the only commercially viable architecture due to Axis 3 ceiling collision risks.

Finally, the integrated framework was realised on a ship's double-bottom block considering robotic welding constraint, achieving an 18.15% reduction in structural mass while maintaining a constant stiffener count and expanding the vertical robotic working envelope to a collision-free 970 mm clearance. The scantlings strictly comply with IACS CSR and Lloyd's Register standards (174.05 MPa stress; 1.1306 buckling load multiplier) with an error margin below 0.5%. This research establishes a definitive roadmap for Robot-Informed Design, concurrently optimising structural efficiency and automated manufacturability to advance global shipbuilding productivity.

Keywords: Robotic Welding, Multi-Objective Structural Optimisation; Ship Production; Ship Structure; Confined Space; Cost Efficiency.

Chapter 1. Introduction

1.1 Background

Ships are large and highly complex engineering products. The design and production of ships lend itself well to the adoption of new technologies, and particularly for ship production process. The construction of complex and bespoke structures is most likely a human dependent activity (Chalkiadakis et al., 2022). When things do not take place according to plan (Wahidi et al., 2022), ‘human error’ is frequently used as an excuse, attributing system failures solely to individual operators (Dekker, 2014; Okumus et al., 2023; Reason, 1990). This, however, masks the reality that the human has been asked to do something that is too hard. More specifically, we may conclude that the human has been tasked with an action that is beyond their capability, their experience, or their training.

The maritime industry is currently undergoing a significant paradigm shift toward Industry 4.0, characterised by the integration of automation and digital twins to enhance productivity and worker safety. Shipbuilding, particularly the assembly of block panels, remains one of the most labour-intensive sectors due to the complexity of the structures and the harsh working environments (Lee, 2013). Among the various manufacturing processes, welding accounts for a substantial portion of the total production time and costs (Wahidi et al., 2021).

While automation has been successfully implemented in open-area welding, such as flat panel lines, the interior of ship structures, specifically the double bottom blocks, presents a formidable challenge. These areas are characterised by "confined

spaces, (Arifin et al., 2023)" often with vertical clearances as low as 1200 mm, congested with stiffeners, girders, and manholes. Manually welding in these restricted compartments not only leads to inconsistent weld quality due to ergonomic constraints but also poses severe occupational health risks to human welders (Okumus et al., 2023).

The integration of advanced automation into the ship block assembly process significantly enhances production efficiency by addressing complex welding requirements across different manufacturing stages (Moghaddam et al., 2018). During the initial open block stage (Kang et al., 2008), welding is primarily executed using a specialised robotic welding gantry, which provides high-precision access to accessible structural joints (Morgado-Estevez et al., 2018). Following this phase, the assembly is turned over and positioned onto the bottom shell, effectively creating a closed block configuration as illustrated in Figure 1-1. This transition necessitates the deployment of robotic welding systems capable of entering the enclosed space to perform critical internal joins (Lee, 2013). A key operational focus within these confined compartments is the execution of the U-shaped welding line process, which secures the longitudinal stiffeners to the bottom floor during the final block assembly phase (Lee et al., 2011). This sequence ensures structural integrity within restricted volumes where traditional manual welding access is severely limited (Jia et al., 2025).

Addressing these issues, particularly the execution of complex U-shaped welding trajectories in restricted compartments, requires advancing the conventional concept of 'Design for Production' toward an integrated 'Design for Automated (Robot-Based) Production' framework. Some research about Automated (Robot-

Based) production has been conducted to increase the capacity of factory such as additive manufacturing integration with topology optimisation methodology for innovative product design (Primo et al., 2017), development of mobile robotic system for ship structure (Lee et al., 2010), and Intelligent inspection robot based on wireless sensor (J. Zhang et al., 2020). Furthermore, automated production is inherently coupled with structural design variables, such as strength-to-weight ratio and production-to-weight cost trade-offs. Therefore, it is crucial to advance from conventional Design for Manufacture (DfM) toward a dedicated Design for Automation (DfA) framework, systematically integrating robotic manufacturing constraints into early-stage structural optimisation to enhance safety, efficiency, and industrial competitiveness in shipbuilding.

Robotic welding undoubtedly improves weld consistency and speeds up production, but traditional design limitations sometimes prevent it from being used in double bottom blocks. Conventionally, structural optimisation for vessels has prioritised mass minimisation and structural compliance under classification society mandates (Lima et al., 2025). However, such traditional approaches often catalyse manufacturing bottlenecks (Putra et al., 2019), characterised by protracted production schedules and inflated labour expenditures (Pribadi et al., 2025). This is particularly evident when non-standard stiffener arrangements are utilised to satisfy structural criteria (Wahidi et al., 2025). Moreover, traditional structural optimisation usually concentrates only on reducing weight, which frequently leads to a higher number of smaller stiffeners. This may save mass, but it also unintentionally lengthens the weld joints overall, making assembly more difficult and prolonging the robotic welding

cycle. These "weight-centric" designs frequently produce scantlings that are manufacture-impenetrable yet structurally sound, severely restricting the required physical clearance for the manipulator and limiting accessible kinematic configurations, which leads to joint-link interferences during automated welding inside 1.2-meter double-bottom compartments (S. Liu et al., 2024).

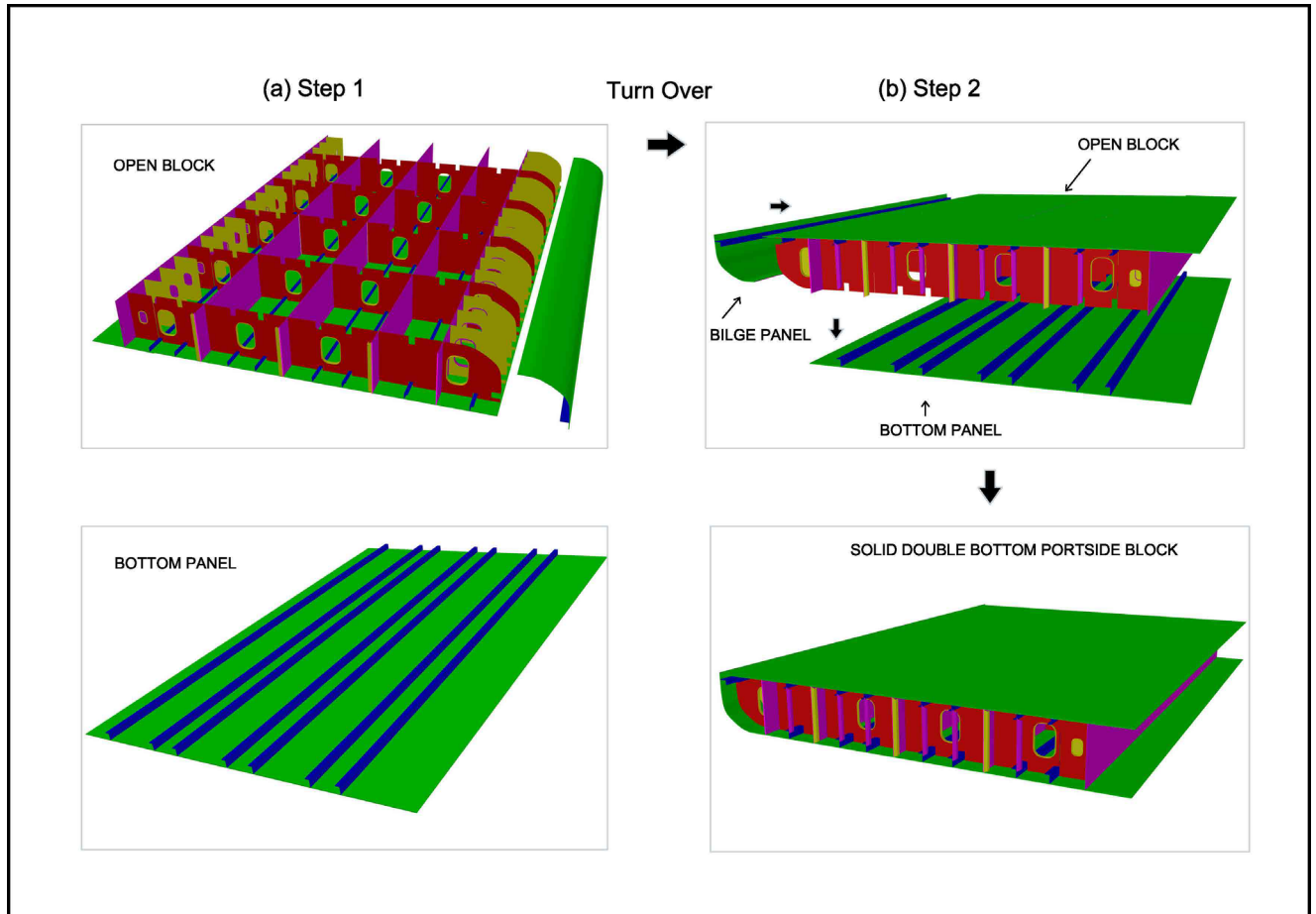


Figure 1-1 Schematic representation of the ship block assembly sequence (a) Step 1: initial assembly of longitudinal stiffeners and transverse bulkheads in an open configuration; (b) Step 2: installation of the inner bottom plate creating a confined "closed block" environment (Wahidi et al., 2023).

Recent advancements in Multi-Objective Structural Optimisation (MOSO) have increasingly leveraged meta-modelling techniques, including Response Surface Methodology (RSM) and Genetic Algorithms, to reconcile divergent objectives such as mass minimisation and structural resilience (Cong et al., 2025). Previous research has established robust foundations in automated FE-based design optimisation (W. Yang et al., 2016) and the enhancement of automated production lines (Mourtzis et al., 2019). Furthermore, various computational strategies have been employed to address structural challenges, ranging from particle swarm optimisation (PSO) (Ehlers & Kujala, 2014) to integrated finite element methods (Ehlers, 2010). Despite these developments, a critical research gap remains: the systematic exclusion of robotic kinematic constraints during the preliminary design phase. Conventional optimisation frameworks predominantly treat manufacturing accessibility as a secondary consideration, often resulting in suboptimal designs that necessitate expensive revisions or bespoke robotic hardware.

As a result, to massively develop this technology in the shipbuilding industry, ship structure optimisation by considering automated (robot-based) production in the development of a smart manufacturing approach needs to be implemented.

1.2 Problem Statement

The primary bottleneck in automating ship block assembly is the traditional "design for strength" approach (Kong et al., 2006), which often overlooks "design for production and automation." Structural optimisation has historically focused on minimising weight to improve fuel efficiency and payload capacity (Ehlers et al., 2015). While weight-centric designs improve material efficiency, within the scope of

stiffened plate optimisation where base plate thickness is minimised, they frequently compensate for lost local bending stiffness by increasing the number of stiffeners (Putra et al., 2019). This layout alteration inadvertently multiplies the total joint volume and assembly handling requirements, thereby increasing production time and costs. Furthermore, such complex configurations frequently render the structure impenetrable for standard industrial manipulators, hindering automated welding efforts.

Current robotic welding technology faces significant kinematic limitations when operating in confined naval environments (Lee et al., 2010). While recent state-of-the-art studies in ship structural optimisation have successfully coupled advanced metaheuristics (such as MOGA, PSO, and surrogate-assisted RSM) with classification rules and production cost models e.g. (Cong et al., 2025; Lima et al., 2025; Y. Wang et al., 2024; Yu et al., 2024), there remains a notable absence of an integrated framework that systematically embeds robotic kinematic constraints, specifically reachability envelopes, joint limits, and dynamic collision avoidance, directly into the preliminary structural scantling optimisation phase. Without bridging structural synthesis with robotic kinematics at this early stage, shipyards are forced to rely on expensive, custom-made robotic gantries or revert to hazardous manual labor in enclosed blocks (D Lee, Ku, et al., 2011; Wahidi et al., 2024).

1.3 Research Questions

This study seeks to answer the following fundamental questions:

1. What is the current state of robotic welding technology in the maritime industry, and what primary design-related barriers hinder its application in complex ship structures?
2. How can virtual modelling and simulation methodologies be utilised to evaluate the technical feasibility and cost-efficiency of ship block assembly processes?
3. How can a structural optimisation framework effectively balance weight minimisation with the reduction of weld lengths inside confined double-bottom compartments by optimising stiffener web height to enhance fabrication safety and lower production costs?
4. How can robotic kinematic constraints and collision risks be accurately assessed within extreme 1200 mm height constraints to determine the most effective mounting configurations?
5. How can a multi-objective optimisation framework dynamically integrate robotic kinematic constraints into the preliminary design phase of ship double-bottom blocks?

1.4 Research Objectives

The main goal of this doctoral research is to develop a holistic framework that bridges the gap between ship structural design and robotic manufacturing capabilities.

The specific objectives are:

1. To conduct a Systematic Literature Review (SLR) to map existing robotic welding techniques and identify the critical design challenges within the maritime sector. (*Addressed in Chapter 2*)

2. To develop a simulation of the ship block assembly process to analyse production flow optimisation and cost estimation through robotic integration. *(Addressed in Chapter 4)*
3. To develop a structural optimisation model aimed at minimising weight and weld lengths to improve safety and manufacturing cost-efficiency by optimising stiffener web height. *(Addressed in Chapter 5)*
4. To establish a Design for Automation Framework to evaluate robot kinematics and collision analysis across multiple mounting positions in confined environments. *(Addressed in Chapter 6)*
5. To formulate a Multi-Objective Structural Optimisation that integrates robotic operational constraints as decisive variables in the design of ship double-bottom scantlings. *(Addressed in Chapter 7)*

1.5 Significance of the Study

The novelty of this study lies in its dual-purpose approach: treating robotic kinematic boundaries as essential design variables alongside optimising weight and strength requirements. Integrating these constraints early in the design cycle enables a substantial reduction in total welding time and limits the need for human presence in confined, dangerous ship compartments. The findings offer a roadmap for "Design for Automation" in the maritime industry, ultimately leading to lower production costs, faster lead times, and enhanced safety standards.

1.6 Research Output

The research output from this Ph.D. thesis has been published and submitted for publication.

Journal and Conference Paper Publication:

1. Wahidi, S. I., Oterkus, S., & Oterkus, E., (2023). Simulation of a Ship's Block Panel Assembly Process: Optimising Production Processes and Costs through Welding Robots. *Journal of Marine Science and Engineering*, 11(8), 1506. <https://doi.org/10.3390/JMSE11081506>. (*Addressed for Research Objective 2 / Detailed in Chapter 4*)
2. Wahidi, S. I., Oterkus, S., & Oterkus, E. (2024). Robotic welding techniques in marine structures and production processes: A systematic literature review. *Marine Structures*, 95 (May 2024), 103608. <https://doi.org/10.1016/j.marstruc.2024.103608>. (*Addressed for Research Objective 1 / Detailed in Chapter 2*)
3. Wahidi, S. I., Oterkus, S., Oterkus, E., Supomo, H., & Pribadi, T. W. (2025). Structural optimisation for minimising weight and welding in confined shipbuilding spaces: Enhancing safety and reducing costs. *Ocean Engineering*, 341, 122779. <https://doi.org/10.1016/j.oceaneng.2025.122779>. (*Addressed for Research Objective 3 / Detailed in Chapter 5*)
4. Wahidi, S. I., Oterkus, S., Oterkus, E., Supomo, H., & Pribadi, T. W., Mursid, O. (2026). Kinematic Evaluation of Multi-Position Robotic Welding in Confined Ship Structures within a Design for Automation (DfA) Framework (Submitted / Under Review in *Ocean Engineering*, Elsevier). (*Addressed for Research Objective 4 / Detailed in Chapter 6*)
5. Wahidi, S. I., Oterkus, S., Oterkus, E. (2026). Robotic Welding Constraints in Multi-Objective Structural Optimisation of Ship Double Bottom Blocks for

Confined Space Applications (Submitted / Second round Review in Ocean Engineering, Elsevier). (*Addressed for Research Objective 5 / Detailed in Chapter 7*)

6. Wahidi, S.I., Oterkus, S., Oterkus, E., Baihaqi, I., Ariesta, R.C., & Supomo, H. (2026). An Optimisation Framework for Integrating Automated Production Constraints into Ship Structure Design (Accepted for Proceeding Paper the 11th International Conference on Marine Technology and will be presented on October 2026). (*Addressed for Research Objective 5 / Detailed in Chapter 7*)

Conference Abstracts and Presentations:

1. Wahidi, S.I., Oterkus, S., Oterkus, E. (2023). Structural Optimisation Considering Automated (Robot-Based) Ship Production. Ocean Energy and Maritime Transport Research Conference 2023 (NAOME OEMT 2023) University of Strathclyde (Glasgow, United Kingdom). (*Addressed for Research Objective 1 & 2 / Detailed in Chapter 2 & 4*).
2. Wahidi, S.I., Oterkus, S., Oterkus, E. (2024). Robotic Welding in Manufacturing Operations for Marine Buildings. In The 7th UK Marine Technology Postgraduate Conference (MTPC) University of Southampton (United Kingdom). April 16 to 17, 2024. (*Addressed for Research Objective 1 / Detailed in Chapter 2*).
3. Wahidi, S.I., Oterkus, S., Oterkus, E. (2024). Robotic Welding and Structural Optimisation for Automated Ship Production in Maritime Industry. Ocean Energy and Maritime Transport Research Conference 2024 (NAOME OEMT 2024)

University of Strathclyde (Glasgow, United Kingdom). (*Addressed for Research Objective 2/ Detailed in Chapter 4*)

4. Wahidi, S.I., Oterkus, S., Oterkus, E. (2025). Multi-Objective Stiffened Plate Optimisation: Minimising Weight and Welding to Reduce Cost and Safety Improvements in Confined Ship Production Process. Ocean Energy and Maritime Transport Research Conference 2025 (NAOME OEMT 2025) University of Strathclyde (Glasgow, United Kingdom). (*Addressed for Research Objective 3 / Detailed in Chapter 5*)
5. Wahidi, S.I., Oterkus, S., Oterkus, E., Supomo, H., & Pribadi, T. W. (2026). Simulation and Implementation of Robotic Welding in Confined Shipbuilding Spaces. The 10th International Conference on Dynamics in Logistics (LDIC 2026) University of Bremen (Germany). February 25 to 27, 2026. (*Addressed for Research Objective 4/ Detailed in Chapter 6*)
6. Wahidi, S.I., Oterkus, S., Oterkus, E., Supomo, H., & Pribadi, T. W. (2026). Simulation-Based Evaluation of Robotic Welding for Optimised Ship Assembly. The 2026 SNAME Maritime Convention (SMC 2026). The Royal Sonesta Houston Galleria, Houston, Texas, USA. Submitted and will be presented on October 29 to 30, 2026. (*Addressed for Research Objective 5 / Detailed in Chapter 7*)

Chapter 2. Literature and Critical Review

2.1 A Systematic Literature Review of Robotic Welding Techniques in Marine Structures and Production Processes

This sub-chapter presents a systematic literature review (SLR) that comprehensively maps the global landscape, state of the art, and inherent technical boundaries of integrating robotic welding technologies within maritime manufacturing. Given the increasing demand for shipyard automation, this review establishes a rigorous taxonomy of existing robotic welding methods, architectural typologies, and marine-grade materials utilised across recent research experiments. By synthesising the quantifiable economic advantages alongside the prevailing kinematic and spatial constraints found in literature, this section delineates the critical research gaps that currently hinder widespread industrial adoption. Ultimately, this comprehensive evaluation serves as the foundational baseline for the 'Design for Automation' (DFA) framework developed in the subsequent phases of this doctoral dissertation.

2.1.1 Background & Significance

The shipbuilding and marine industry play a crucial role in global trade and transportation, requiring the construction of robust and reliable vessels and marine structures. The welding process is a critical aspect, as it ensures structural integrity and longevity. However, traditional manual welding methods often suffer from limitations such as inconsistent quality, low productivity, and safety concerns. To overcome these challenges and improve marine structure and production processes, the integration of technological innovation has gained significant attention in the maritime industry.

The advent of technological innovation has substantially reshaped many industries, one of which is the maritime sector. This transformation has significantly impacted marine structure construction and production processes, largely driven by the adoption of automation and robotics (Muhuri et al., 2019). Among various automated technologies, robotic welding has emerged as a crucial technique, offering numerous advantages such as improved quality, efficiency, and safety (Javaid et al., 2021).

Robotic welding, a process where automated programmable tools perform welding operations, has been extensively used in different industrial applications (Kah et al., 2015). In marine structures and production processes, this technology offers promising potential for enhancing manufacturing efficiency and quality (Loukas et al., 2021). The effectiveness of robotic welding in this sector, however, is influenced by many factors including process parameters, welding methodologies, material properties, and environmental conditions (L. Yang et al., 2021).

The utilisation of robotic welding presents numerous benefits in comparison to traditional welding methods, such as enhanced levels of accuracy, consistency, and productivity (Andersen et al., 2016). The implementation of robotic automation in the welding process enables the attainment of consistently high-quality welds, leading to improved structural integrity and a decrease in the need for rework (Dharmawan et al., 2014). Moreover, the incorporation of automated welding systems has the potential to enhance productivity through the reduction of reliance on human labour, the mitigation of overall production duration, and the identification of opportunities for cost reduction

(Wahidi et al., 2023). However, there are still challenges and limitations that need to be addressed to fully exploit the potential of robotic welding in the marine industry.

Existing research has focused on various aspects of robotic welding in marine applications. For example, studies have investigated the microstructure, mechanical properties, and corrosion behaviour of materials used in robotic welding, such as Incoloy 825 (Rajkumar et al., 2022), Inconel-625 (Ravi et al., 2020), and Super Duplex Stainless-Steel (SDSS) (Sales et al., 2022). These studies provide valuable insights into the suitability of these materials for marine applications and the effects of the welding process on their properties.

Furthermore, research has been conducted on the development of robotic systems for specific tasks in marine welding, such as cooperative mobile robots for fit-out operations inside ship superstructures (Andersen et al., 2016), portable robotic welding platforms for large-scale structures (Dharmawan et al., 2014), and mobile robotic systems for working in the double-hulled structure of a ship (Lee et al., 2010). These studies address the challenges of working in complex and confined spaces in the marine environment and propose innovative solutions for efficient and safe welding operations (Wahidi et al., 2022).

Other research has focused on improving the performance and quality of robotic welding through advanced techniques and technologies. For example, studies have investigated the use of vision-assisted robotic finishing (Gurdal et al., 2019), laser keyhole weld termination regimes (Lai et al., 2020), and sensor-enabled multi-robot systems (Vasilev et al., 2021) to enhance the accuracy, control, and reliability of

welding processes. These studies contribute to the development of intelligent and adaptive robotic welding systems for marine applications.

Additionally, research has explored the optimisation of welding parameters and process planning strategies for robotic welding in marine structures. Studies have investigated the optimisation of process parameters for steel EN24T (Ali et al., 2022), the determination of optimum welding parameters for steels used in underwater marine systems (Oikonomou & Aggidis, 2019), and the development of optimal noise filter algorithms for laser vision systems in GMA welding (Q. Q. Wu et al., 2014). These studies aim to improve the efficiency, quality, and cost-effectiveness of robotic welding in the marine industry.

To date, numerous studies have investigated the use of robotic welding in marine applications for marine structures and production processes. These studies have explored various aspects, such as different welding techniques, process parameters, quality assessment methods, and productivity enhancement strategies. However, a comprehensive understanding of the existing knowledge, trends, and research gaps in this field is necessary to guide future research efforts and technological advancements.

Considering this context, this study employed a systematic review approach to locate and assess scholarly literature pertaining to the utilisation of robotic welding in marine structures and production processes. The subsequent research inquiries served as the guiding framework for the review:

1. Which welding methods are applied using robotic welding technology?
2. Which types of robotic welding were used in the cited research experiments?
3. Which materials were processed in the reported research and experiments?

4. What potential advantages can be derived from the utilisation of the indicated robotic welding?
5. What are the current obstacles and deficiencies that hinder its widespread implementation in the industry?

The main objectives of this systematic literature review are threefold: firstly, to identify and classify various robotic welding techniques employed in marine applications, including arc welding, laser welding, hybrid welding, and friction stir welding; secondly, to assess the types and levels of robotic welding mentioned in the literature; and thirdly, to explore the processed materials, including steel, aluminium, nickel-aluminium bronze, and other different metal alloys. Additionally, this review investigates the benefits that could be achieved by using the identified robotic technologies reported in the literature. Moreover, it examines the challenges and limitations faced in implementing robotic welding systems in the maritime sector, including complex marine structures, welding of dissimilar materials, environmental conditions, and combination of building task repeatability and robot control.

The rationale for the review on robotic welding techniques in marine structures and marine production processes is to gather and synthesise existing knowledge in this field. By synthesising the findings of various studies, this study will provide a comprehensive understanding of the current state-of-the-art, highlight research gaps, and propose recommendations for further research and development. Ultimately, the integration of robotic welding systems in the maritime industry has the potential to

significantly improve marine production processes, leading to enhanced efficiency, quality, and competitiveness.

As the maritime industry increasingly embraces advanced materials and intricate designs, the evolution of robotic welding techniques becomes pivotal in addressing the complexities associated with diverse materials, joint configurations, and varying thicknesses. Moreover, the systematic literature review sheds light on the current state of research, showcasing the industry's trajectory and emphasising the critical need for further advancements. By understanding the intricacies of these techniques, the industry can harness their full potential, ensuring a more efficient, reliable, and sustainable future in marine construction.

2.1.2 Methodology

The methodology section outlines the systematic approach employed in conducting the literature review. The outline is structured into two components: an overview of the search strategy and a detailed selection process. The former provides insight into the overarching strategy designed to identify relevant literature, while the latter delves into the specific steps undertaken for the selection of studies.

2.1.2.1 Overview of the search strategy

In order to conduct this inquiry, an approach based on systematic review was employed. A systematic literature review (SLR) is a rigorous and comprehensive analysis of the available literature pertaining to a certain subject. The process entails a methodical exploration and evaluation of pertinent scholarly works, adhering to a predetermined approach in order to uphold objectivity and the ability to replicate findings (Bottani et al., 2022; Chalkiadakis et al., 2022; Gharbia et al., 2020; Ozturk

& Cicek, 2019). The methodology employed for conducting this systematic literature review on "Robotic Welding Techniques in Marine Structures and Production Processes" was formulated in accordance with the recommendations outlined by PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to guarantee a thorough and impartial review (Page et al., 2021).

The probability of bias in the selection of publications is a limitation of the systematic review methodology. The application of inclusion and exclusion criteria may also result in the omission of pertinent papers that do not meet these criteria. Many advancements in the field of robotic welding in marine application are driven by practitioners who may not publish in journals or conference proceedings. Consequently, it is possible that pertinent studies published in grey literature or elsewhere were overlooked during the search.

The search strategy was developed to identify all relevant publications related to robotic welding in marine applications. Several electronic databases, including ScienceDirect, IEEE Xplore, Scopus, and Web of Science, were utilised (Martín-Martín et al., 2018). To ensure scientific rigor and replicability, the search queries were executed using combinations of title, abstract, and keyword with the search terms included combinations and variants of "robotic welding", "marine structures", "shipbuilding", and "production processes".

To select the most relevant publications, inclusion and exclusion criteria were established. The inclusion criteria focused on publications that specifically addressed robotic welding techniques in marine structures and production processes. Additionally, publications had to be written in English and published within the past

15 years (2007-2022) to ensure currency. Exclusion criteria were applied to filter out irrelevant publications that were unrelated to robotic welding, marine applications, or marine structure and marine production processes.

The initial screening process consisted of evaluating the titles and abstracts of the selected publications in order to ascertain their relevance to the research subject. The publications that were chosen were subsequently acquired in their entirety for further evaluation. Every publication underwent a comprehensive evaluation process, wherein the inclusion and exclusion criteria were meticulously applied to determine its suitability for inclusion in the systematic literature review. (Moher et al., 2016).

The quality and relevance of the selected publications were assessed using evaluation criteria such as the rigor of research methodology, the validity of findings, and the reputation of the authors and publishing venues. This assessment helped to ensure that high-quality and reliable publications were included in the systematic literature review (Munn et al., 2018).

Data were extracted from the selected publications, including information such as authors, title, publication year, research objectives, methodologies, key findings, and the type of robotic welding technique applied. This data extraction process enabled the organisation and synthesis of the information obtained from the publications, facilitating the identification of common themes, trends, and research gaps, as well as examining the implications and potential future directions suggested by the reviewed literature. The data were summarised and analysed descriptively to identify common themes, advancements, and challenges related to robotic welding in marine applications.

The findings of the systematic literature review were organised and presented in a coherent manner, following the structure of the research paper. The methodology, key findings, and insights gained from the reviewed literature were summarised, and any implications and recommendations were discussed.

2.1.2.2 Detailed selection process

The flow diagram depicted in Figure 2-1 presents a comprehensive outline of the selection procedures conducted for this review, adhering to the guidelines set forth in the PRISMA declaration (Page et al., 2021) and utilising the PRISMA2020 product (Haddaway et al., 2022). The selection process proceeded in the following manner: The three stages of the screening process include: 1) record identification, 2) title and abstract screening, and 3) full-text screening according to predetermined eligibility criteria. Our analysis focused exclusively on peer-reviewed articles, as this approach guarantees that the papers published in academic journals and conferences address pertinent research inquiries and present significant findings (Kelly et al., 2014).

The systematic literature review selection process commenced with the identification of 956 published works from various electronic databases, namely ScienceDirect, IEEE Xplore, Scopus, and Web of Science. Subsequent to this initial retrieval, 17 duplicate records were removed. Additionally, 83 records were deemed ineligible and automatically excluded using the automated screening and metadata-filtering algorithms in Mendeley Reference Manager. The tool's rule-based engine filtered records based on objective exclusion criteria, automatically purging entries categorised as non-English documents, patent entries, conference summaries without technical data, and publication years falling outside the 2007–2022 window. This

automated screening stage ensured that only relevant technical articles (751 records) advanced to the title and abstract evaluation phase.

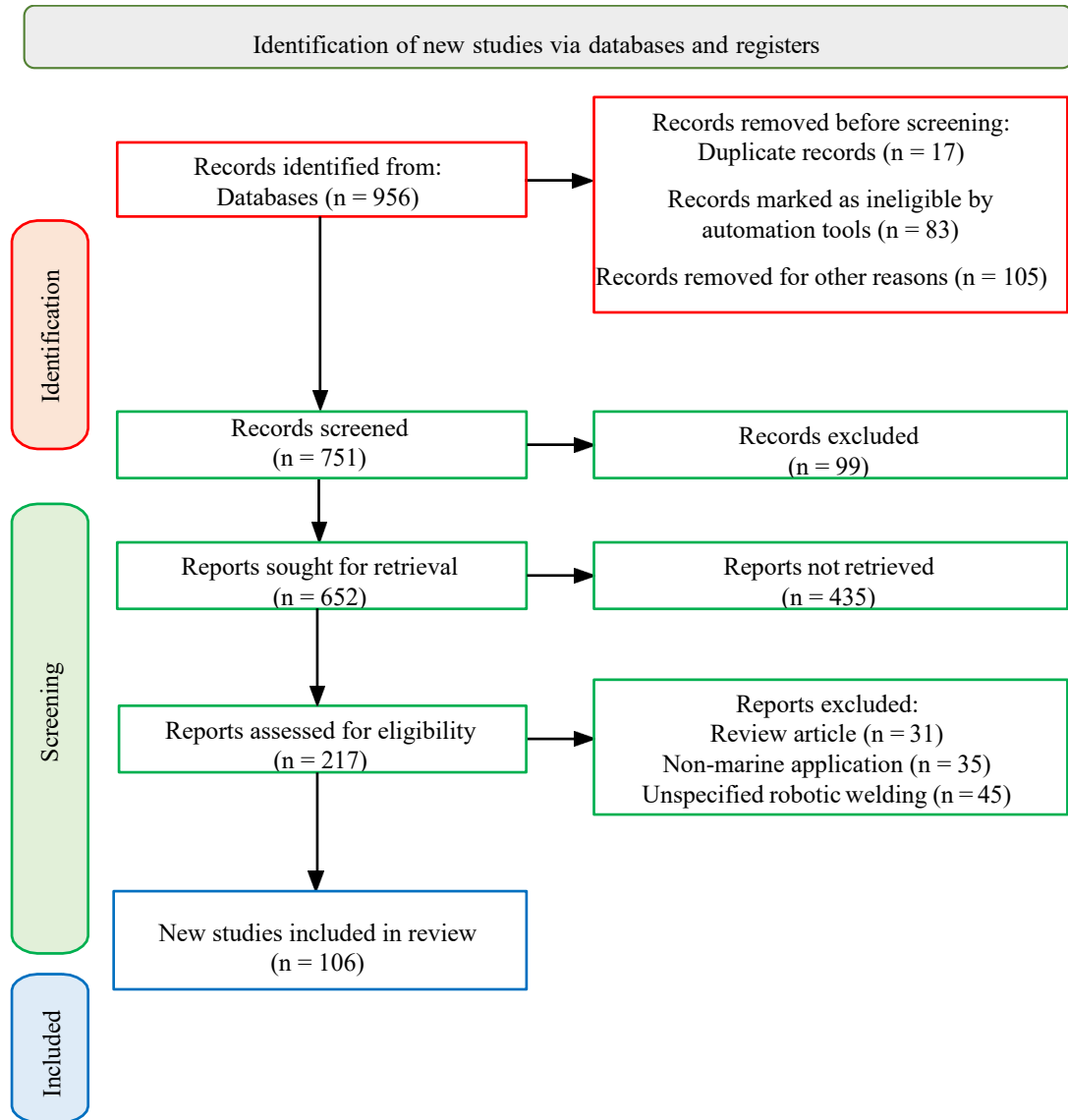


Figure 2-1 Process flow diagram for a systematic literature review (PRISMA flowchart).

In categorising the identified literature, an important technical distinction must be drawn between conventional joining processes and additive manufacturing technologies. Techniques such as Gas Metal Arc Welding (GMAW), Flux-Cored Arc

Welding (FCAW), and Submerged Arc Welding (SAW) are historically deployed as fusion joining processes, primarily dedicated to securing plate-to-plate and plate-to-stiffener boundary seams. In contrast, Wire Arc Additive Manufacturing (WAAM) operates as a layer-by-layer material deposition technique aimed at component fabrication and geometry generation.

WAAM was intentionally included alongside conventional joining methods within this systematic review for two fundamental technical reasons: First, on an operational and kinematic level, WAAM directly employs the identical electric arc thermal sources and wire-feed hardware as GMAW/GTAW, operating via the same 6-axis articulated industrial robotic architectures, multi-pass path-planning algorithms, and heat management principles. Second, in the context of contemporary Shipbuilding 4.0, WAAM is increasingly integrated into shipyard fabrication streams as a hybrid manufacturing solution, used to produce complex bespoke structural nodes, localised stiffening geometries, and thick brackets that are subsequently welded onto main ship block assemblies via conventional arc methods. Distinguishing yet concurrently analysing both approaches provides a comprehensive mapping of automated arc-based robotic deposition in modern maritime construction.

The screening stage employed four stringent inclusion and exclusion criteria. The first criterion was relevance; papers that did not focus on robotic welding in marine applications were immediately excluded. This led to the elimination of works focusing on different types of structures, such as those concerned with robotic applications in the automotive and land-building sectors. The second criterion

considered the specificity of the content; papers that failed to clearly specify robotic welding details and those merely providing review articles were also excluded.

After rigorous application of these criteria, the final selection resulted in a substantial collection of 106 articles. This curated group of papers forms the basis for our systematic literature review, providing a comprehensive understanding of robotic welding applications in the marine industry.

2.1.3 Results

The search and selection procedure yielded a cumulative count of 106 articles that were incorporated into the review. The search process involved identifying relevant articles from various sources, including academic journals and conference proceedings. The selection process involved evaluating the relevance and quality of the articles based on their titles, abstracts, and full texts.

The review's articles address a wide range of subjects relevant to welding in the shipbuilding sector. The utilisation of robotic welding systems, additive manufacturing methods, laser welding, arc welding, and the mechanical characteristics of welded connections are a few of the important topics covered. The articles also cover a variety of welding-related topics, including welding flaws, process parameters, and the impact of various variables on the calibre of the welds.

2.1.3.1 Summary of Selected Articles

This systematic literature review report provides a comprehensive summary of the collected articles, as depicted in Figure 2-2. The study includes a comprehensive analysis of various sources, with approximately 75% of the data sourced from journal

articles and the remaining 25% from conference proceedings, as highlighted in Figure 2-3.

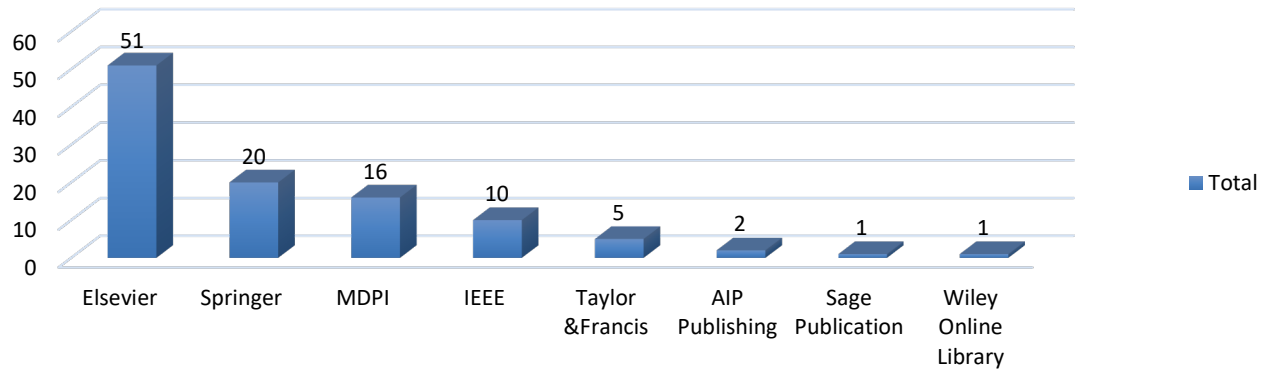


Figure 2-2 Distribution of articles according to the publisher.

The analysis of the sources revealed that the majority of the reviewed articles, accounting for 51 articles, were obtained from Elsevier. Following Elsevier, we found significant contributions from other reputable publishers, such as Springer, MDPI, and IEEE, ranging from 10 to 20 articles each, with 20, 16, and 10 articles, respectively. Taylor & Francis and Wiley Online Library contributed five and one article, respectively, while the literature review yielded two articles from AIP Publishing and one article from Sage Publications. The high representation of articles from Elsevier highlights its prominence as a major publisher in the field, while contributions from other notable publishers underscore the breadth of research in this area.

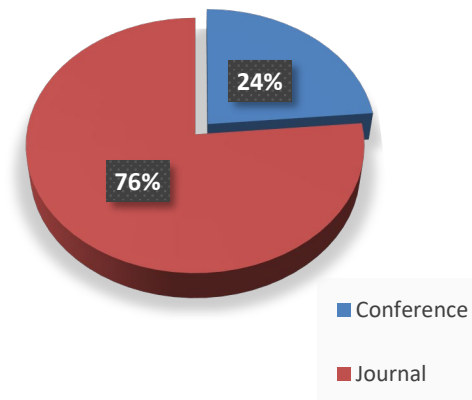


Figure 2-3 Proportion of journal articles and conference papers obtained for review.

According to the year of publication, publications referring to robotic welding in marine applications show a fluctuating trend, with one to five articles being published per year from 2007 to 2016. Starting in 2017, there was a considerable increase, with the count moving from 6 papers to 10 in 2018. Despite a slight decline in 2019, the trend continued to rise, reaching a total of 26 articles in 2022. As illustrated in Figure 2-4, this pattern indicates an increasing popularity of research related to this topic.

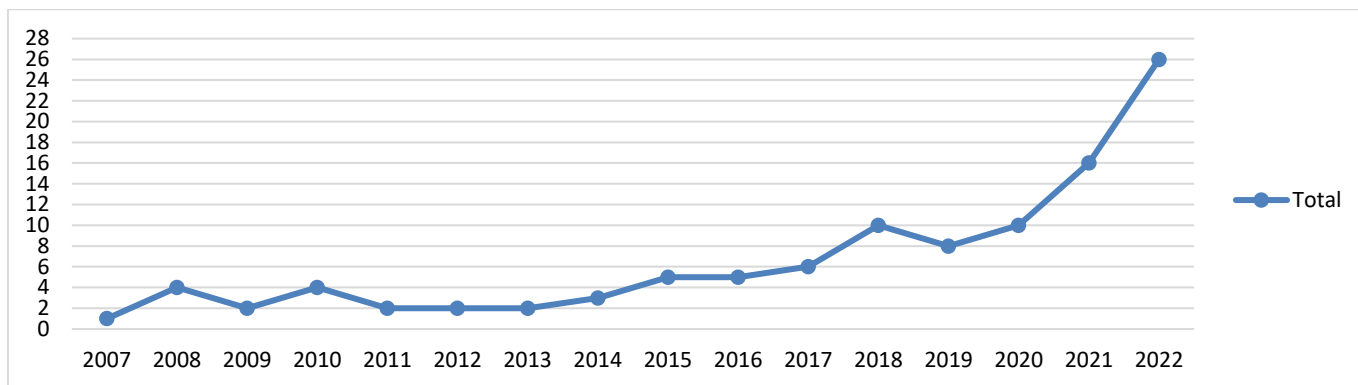


Figure 2-4 Number of publications per year after selection.

Table 2-1 presents the number of publications in respect to journals. Overall, there are 81 articles from journal publications or about 76 per cent of the total article. Accordingly, approximately 41 per cent of robotic welding in marine applications studies were published in five journals including Journal of Manufacturing Processes, The International Journal of Advanced Manufacturing Technology, Robotics and Computer-Integrated Manufacturing, Metals, and Marine Structures. In addition, several articles on this topic were obtained from journals related with maritime field including Marine Structures, Journal of Marine Science and Engineering, Ocean Engineering, Journal of Marine Science and Technology, and Ships and Offshore Structures.

Table 2-1 Number of publications by journal.

Journal	Publisher	References	Article
Journal of Manufacturing Processes	Elsevier	(C. Chen et al., 2022; Gibson et al., 2014; He et al., 2020; Kershaw et al., 2021; Lai et al., 2020; W. Liu et al., 2022; Loukas et al., 2021; Tianying et al., 2021; K. Zhang et al., 2018)	9
The International Journal of Advanced Manufacturing Technology	Springer	(S. N. Ahmad et al., 2022; M. Kazasidis et al., 2021; M. E. Kazasidis & Pantelis, 2017; Le et al., 2017; Liao et al., 2022; Tran et al., 2021; L. Wang et al., 2022; Y. Zhang et al., 2019)	8
Robotics and computer-Integrated Manufacturing	Elsevier	(Chang et al., 2012; X. Chen et al., 2018; Lee, 2013; Lee et al., 2010; Lee et al., 2011; Zheng, An, et al., 2022; Zheng, Xing, et al., 2022)	7
Metals	MDPI	(Ben et al., 2022; J. Kim et al., 2020; S. Liu et al., 2022; Sales et al., 2022; H. Zhang et al., 2022)	5
Marine Structures	Elsevier	(Papatheocharis et al., 2020; Pradhan et al., 2022; Rong, Mi, et al., 2018; P. Zhang et al., 2015)	4
Journal of Marine Science and Engineering	MDPI	(D. S. Kim et al., 2021; Woo & Kitamura, 2020; Q. Wu et al., 2021)	3
Sensors	MDPI	(B. Hong et al., 2021; Park et al., 2009; Vasilev et al., 2021)	3

Journal	Publisher	References	Article
Journal of Marine Science and Technology	Springer	(Ryu et al., 2009; Sanders et al., 2012)	2
Welding International	Taylor & Francis	(Cabral et al., 2015; Lezzi & Costa, 2013)	2
Welding in the World	Springer	(Queguineur et al., 2018; Uemura et al., 2022)	2
Additive Manufacturing	Elsevier	(Dharmendra et al., 2019; Shen et al., 2018)	2
Materials	MDPI	(D. Ding et al., 2016; Świerczyńska & Landowski, 2020)	2
Ocean Engineering	Elsevier	(Hashemzadeh et al., 2022)	1
Ships and Offshore Structures	Taylor & Francis	(Taşdemir & Nohut, 2020)	1
Neural Computing and Applications	Springer	(Zhou et al., 2021)	1
Robotics and Autonomous systems	Elsevier	(Lee et al., 2011)	1
Journal of Cleaner Production	Elsevier	(Bekker & Verlinden, 2018)	1
Vacuum	Elsevier	(Rajkumar et al., 2022)	1
Advanced Engineering Materials	Wiley Online Library	(Pittner & Rethmeier, 2022)	1
Optics & Laser Technology	Elsevier	(Kumar et al., 2017)	1
Buildings	MDPI	(Dörrie et al., 2022)	1
Science and Technology of Welding and Joining	Taylor & Francis	(Long et al., 2022)	1
CIRP Journal of Manufacturing Science and Technology	Elsevier	(Sasikumar et al., 2022)	1
Infrared Physics & Technology	Elsevier	(Long et al., 2021)	1
Journal of Materials Engineering and Performance	Springer	(Qi et al., 2022)	1
International Journal of Mechanical Sciences	Elsevier	(Rong, Lei, et al., 2018)	1
Journal of Materials Processing Tech.	Elsevier	(Rong, Xu, et al., 2018)	1
Computer-Aided Design	Elsevier	(Oh et al., 2010)	1
Proc. IMechE, Part E: Journal of Process Mechanical Engineering	Sage Publication	(Pravin Kumar et al., 2022)	1
Processes	MDPI	(H. K. Lee et al., 2020)	1
Defence Technology	Elsevier	(Choudhary et al., 2019)	1
European Journal of Mechanics / A Solids	Elsevier	(Ermakova et al., 2022b)	1
Journal of Iron and Steel Research International	Springer	(Yin et al., 2021)	1
Fusion Engineering and Design	Elsevier	(Xin et al., 2019)	1
Materials Letters	Elsevier	(Kannan et al., 2022)	1
Sustainability	MDPI	(Epping & Zhang, 2018)	1
Materials Science and Technology	Taylor & Francis	(Ravi et al., 2020)	1
The Journal of The Minerals, Metals & Materials Society (TMS)	Springer	(Jurić et al., 2019)	1
Mechatronics	Elsevier	(Xia et al., 2021)	1
Wear	Elsevier	(Pravin Kumar & Siva Shanmugam, 2020)	1

Journal	Publisher	References	Article
Metallurgical and Materials Transactions B	Springer	(L. Wang et al., 2021)	1
International Journal of Precision Engineering and Manufacturing	Springer	(K. Kim et al., 2010)	1
Engineering Failure Analysis	Elsevier	(Ermakova et al., 2022a)	1
Materials & Design	Elsevier	(G. F. Sun et al., 2017)	1
Grand Total			81

The total number of publications that were related to conference proceedings is presented in Table 2-2. There are a total of 25 articles that were published in the conferences, which accounts for around 24% of the overall number of articles. As a result, approximately fifty percent of the research on robotic welding used in marine applications has been published in the proceedings of five different conferences. These conferences are The International Federation of Automatic Control Proceedings, Materials Today: Proceedings, Procedia Engineering, and Procedia Manufacturing. In addition, the AIP Conference Proceedings has also included some of this research.

Table 2-2 Number of publications by conference proceeding.

Conference	Publisher	References	Article
The International Federation of Automatic Control Proceedings	Elsevier	(Kang et al., 2008; J. Kim et al., 2008; T.-W. Kim et al., 2008; K.-Y. Lee et al., 2008)	4
Materials Today: Proceedings	Elsevier	(Gufran et al., 2022; Oikonomou & Aggidis, 2019; Rautio et al., 2019)	3
Procedia Engineering	Elsevier	(Srikanth et al., 2017; Q. Q. Wu et al., 2014)	2
Procedia Manufacturing	Elsevier	(Ferreira et al., 2017; Gurdal et al., 2019)	2
AIP Conference Proceedings	AIP Publishing	(A. Ahmad, 2021; Narenthiran et al., 2022)	2
Mexican International Conference on Artificial Intelligence	IEEE	(Romero-Hdz et al., 2016)	1
Sixth International Conference on Natural Computation (ICNC)	IEEE	(Mao et al., 2010)	1
International Conference on Control Automation Robotics & Vision (ICARCV)	IEEE	(Dharmawan et al., 2014)	1
International Conference on Industrial Technology (ICIT)	IEEE	(Andersen et al., 2015)	1

Conference	Publisher	References	Article
Iberian Robotics Conference	Springer	(Morgado-Estevez et al., 2018)	1
International Conference on Intelligent Robots and Systems (IROS)	IEEE	(Ahmed et al., 2016)	1
International Conference on Control and Automation	IEEE	(Y. H. Shi et al., 2007)	1
Conference on Emerging Technologies & Factory Automation (ETFA)	IEEE	(Y. Wu et al., 2015)	1
International Workshop on Advanced Motion Control (AMC)	IEEE	(Xia et al., 2016)	1
International Conference on Control, Automation and Information Sciences (ICCAIS)	IEEE	(F. Gao et al., 2015)	1
Light Metals	Springer	(Sales & Ricketts, 2019)	1
International Symposium on Robot and Human Interactive Communication (RO-MAN)	IEEE	(Andersen et al., 2016)	1
Grand Total			25

The analysed articles have been systematically categorised into three distinct research areas, each aligned with its primary objectives. These categories encompass production and welding processes, structural and mechanical properties, and the parametric development of robotic welding techniques, as clearly delineated in

Table 2-3. In total, the compilation comprises a comprehensive collection of 43 articles dedicated to the exploration of production and welding processes, an in-depth examination of 40 articles focusing on the intricate realm of structural and mechanical properties, and a dedicated selection of 23 articles delving into the realm of advancements in parametric robotic welding development. This classification allows for a comprehensive and organised overview of the diverse research efforts undertaken within these domains, shedding light on the multifaceted landscape of advancements in this field.

Table 2-3 Research areas and their included topics.

Research areas	Included Topics	References
Production and Welding Processes (43 articles)	Production and assembly process, weld bead geometry, workspace analysis, life cycle assessment, welding process, space posture of arc welding guns, post-production analysis, decision-making, welding sequence optimisation, CAD integrated weld paths, vision-assisted for corner joints, welding in intersecting joint, filling shape-varying geometry, wireless teaching pendant, weld formation, path planning and forming, welding position.	(A. Ahmad, 2021; Andersen et al., 2016; Bekker & Verlinden, 2018; Cabral et al., 2015; C. Chen et al., 2022; Choudhary et al., 2019; Dharmawan et al., 2014; Dörrie et al., 2022; Epping & Zhang, 2018; Ferreira et al., 2017; Gibson et al., 2014; Gurdal et al., 2019; Kang et al., 2008; J. Kim et al., 2008; T.-W. Kim et al., 2008; Le et al., 2017; D. Lee, 2013; D. Lee et al., 2010; D. Lee, Ku, et al., 2011; D. Lee, Seo, et al., 2011; H. K. Lee et al., 2020; K.-Y. Lee et al., 2008; Lezzi & Costa, 2013; Liao et al., 2022; W. Liu et al., 2022; Morgado-Estevez et al., 2018; Oh et al., 2010; Pittner & Rethmeier, 2022; Pradhan et al., 2022; Romero-Hdz et al., 2016; Ryu et al., 2009; Shen et al., 2018; Srikanth et al., 2017; Taşdemir & Nohut, 2020; Tianying et al., 2021; Tran et al., 2021; Uemura et al., 2022; Q. Wu et al., 2021; Y. Wu et al., 2015; Xia et al., 2021; H. Zhang et al., 2022; K. Zhang et al., 2018; Y. Zhang et al., 2019)
Structural and mechanical properties (40 articles)	Microstructure and mechanical properties, structural analysis, fatigue resistance, corrosion-fatigue crack growth, wear and corrosion resistance, dynamic behaviour, micro and macro examination, forming	(S. N. Ahmad et al., 2022; Ben et al., 2022; Dharmendra et al., 2019; D. Ding et al., 2016; Ermakova et al., 2022a, 2022b; Hashemzadeh et al., 2022; He et al., 2020; Jurić et al., 2019; Kannan et al., 2022; M. Kazasidis et al., 2021; M.

Research areas	Included Topics	References
	appearance, thermomechanical analysis, electrochemical evaluation, material composition, fracture mechanism.	E. Kazasidis & Pantelis, 2017; D. S. Kim et al., 2021; J. Kim et al., 2020; Kumar et al., 2017; Lai et al., 2020; S. Liu et al., 2022; Long et al., 2021; Papatheocharis et al., 2020; Pravin Kumar et al., 2022; Pravin Kumar & Siva Shanmugam, 2020; Qi et al., 2022; Queguineur et al., 2018; Rajkumar et al., 2022; Rautio et al., 2019; Ravi et al., 2020; Rong, Lei, et al., 2018; Rong, Mi, et al., 2018; Rong, Xu, et al., 2018; Sales et al., 2022; Sales & Ricketts, 2019; Sasikumar et al., 2022; G. F. Sun et al., 2017; Świerczyńska & Landowski, 2020; L. Wang et al., 2021, 2022; Woo & Kitamura, 2020; Xin et al., 2019; Yin et al., 2021; P. Zhang et al., 2015)
Parametric development (23 articles)	Welding seam tracking, corner-finding algorithm, feedforward filling control, optimum welding parameter, hybrid machine learning, hybrid offline programming, seam-tracking algorithm, intuitive task programming, structured-light vision system, cost-function driven adaptive welding, laser vision sensing, noise filter algorithm, sensor-enabled robot system, parametric evaluation, object detection and motion planning, deposition	(Ahmed et al., 2016; Andersen et al., 2015; Chang et al., 2012; X. Chen et al., 2018; F. Gao et al., 2015; Gufran et al., 2022; B. Hong et al., 2021; Kershaw et al., 2021; K. Kim et al., 2010; Long et al., 2022; Loukas et al., 2021; Mao et al., 2010; Narenthiran et al., 2022; Oikonomou & Aggidis, 2019; Park et al., 2009; Sanders et al., 2012; Y. H. Shi et al., 2007; Vasilev et al., 2021; Q. Q. Wu et al., 2014; Xia et al., 2016; Zheng, An, et al., 2022; Zheng, Xing, et al., 2022; Zhou et al., 2021)

Research areas	Included Topics	References
	ratio, active heat management, end-effector measurement system.	

Figure 2-5 depicts the distribution of publications based on the geographic location of the primary author's affiliated institute. The majority of scholarly publications pertaining to the subject were authored by scholars based in China, with a total of 31 papers, followed by Korea, India, United Kingdom, Singapore, and Australia which has 17,12,8,6, and 4 articles, respectively. When examining the geographic distribution of scholarly papers pertaining to research areas, it becomes apparent that academics in Korea are at the forefront of investigating marine production processes through the utilisation of robotic welding techniques, as evidenced by the publication of 11 articles on this subject, followed by China with 9 articles. Meanwhile, researchers from China, who led the research in this field, focused on 14 papers observing the structural and mechanical properties of materials processed using robot welding technology, followed by India with 7 articles. Research that focuses on parametric developments for the robot technology used is also dominated by China with 8 papers followed by Korea, India, United Kingdom and Singapore (2 – 4 papers each).

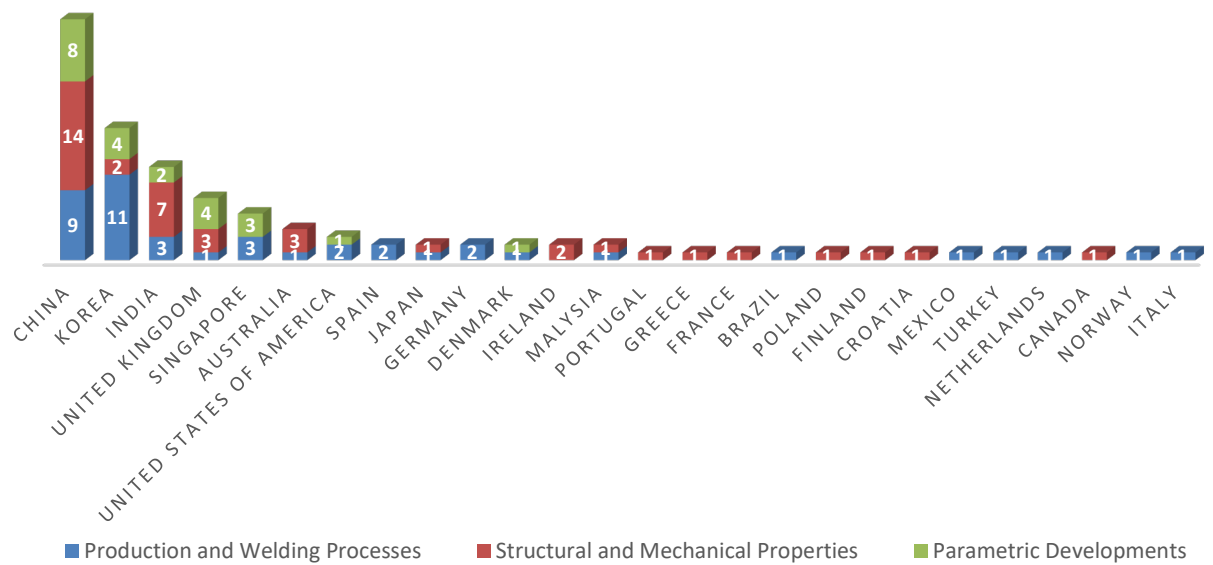


Figure 2-5 Number of publications by geographical distribution across their research areas.

2.1.3.2 The network, overlay and density visualisation of keywords

To visualise and examine the relationship between research keywords and published documents based on occurrences and total link strength we have performed a network analysis. Mainly, there are three types of visualisations which were developed by using VOS viewer including density visualisation, network visualisation, and overlay visualisation. Co-occurrence analysis was done based on a criterion of author-provided keywords. All the keywords (331), out of these selected keywords (30) are threshold based on a minimum of three co-occurrences. As a result, the top 30 keywords used by the authors' in robotic welding in marine applications articles are shown in Table 2-4.

Table 2-4 Keywords occurrences and link strength in the cited articles.

No	keywords	occurrences	total link strength
1	wire arc additive manufacturing	20	28
2	welding	17	28
3	microstructure	15	37
4	robotic welding	15	14
5	mechanical properties	14	33
6	laser welding	11	16
7	additive manufacturing	8	14
8	mobile welding robotic	8	12
9	shipbuilding	8	13
10	corrosion	6	12
11	hybrid laser arc welding	6	9
12	residual stress	6	9
13	double hull structure	5	10
14	gas metal arc welding	5	4
15	multi-pass welding	5	7
16	robot vision systems	5	6
17	seam tracking	5	6
18	finite element analysis	4	4
19	mechanism design	4	9
20	nickel aluminium bronze	4	9
21	optimisation	4	7
22	path planning	4	5
23	flux-cored arc welding	3	2
24	genetic algorithm	3	2
25	high-strength steel	3	9
26	offline programming	3	5
27	robot	3	3
28	robotics	3	3
29	shipyard	3	7
30	tensile	3	3

Figure 2-6 depicts the density map of co-occurrence keywords, where the colour of the nodes indicates the frequency of the terms. Each point in the visualisation of item density is coloured according to the item density at that location. The closer the

colour of a point to yellow, the greater the number of items in its vicinity and the greater the weights of those items. On the other hand, the closer a point's colour to blue, the fewer neighbouring items there are and the lighter their weights, the smaller the number of items in its vicinity. According to the occurrences, “wire arc additive manufacturing” is the most used keyword with a total of 20 occurrences. Other keywords which have more than 10 occurrences are “welding”, “microstructure”, “robotic welding”, “mechanical properties”, and “laser welding” with total occurrences of 17, 15, 15, 14, and 11, respectively. However, based on the total link strength (TLS), “microstructure” has the highest TLS with 37 links, followed by “mechanical properties,” “wire arc additive manufacturing,” and “welding” with total link strengths of 33, 28, and 28, respectively.

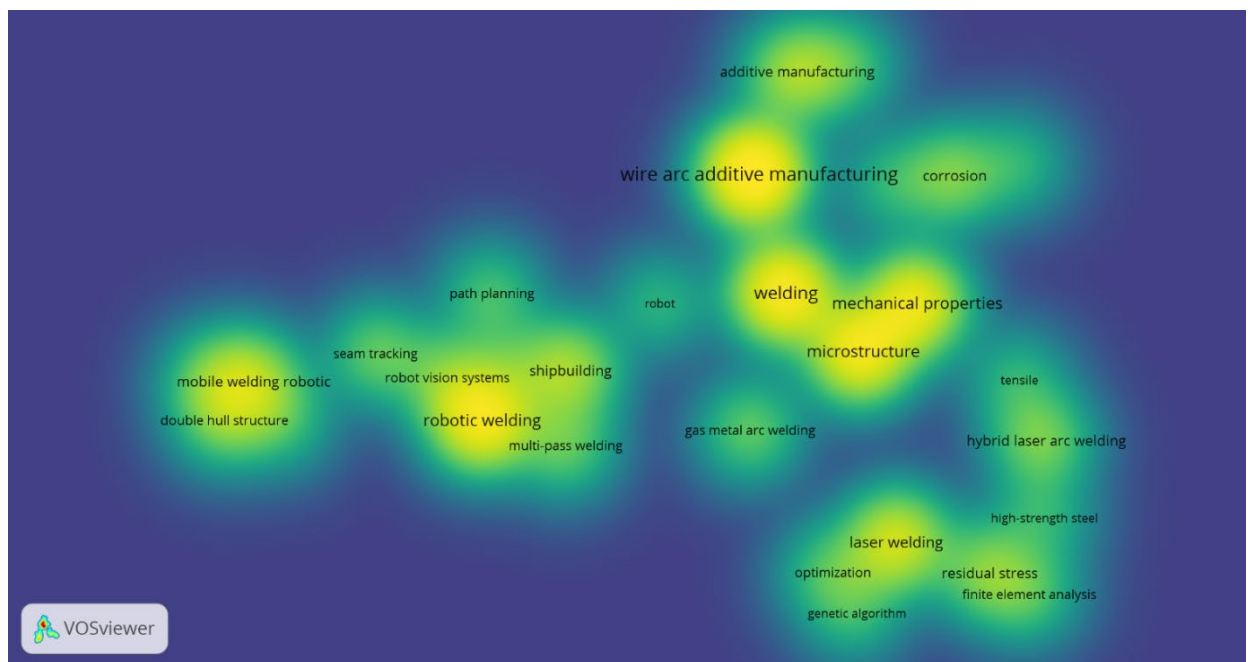


Figure 2-6 Density visualisation of keywords co-occurrence with minimum three occurrences.

VOS viewer generates two separate maps for network and overlays visualisation. Both visualisations employ a two-dimensional distance-based map that illustrates the degree of object relationships based on their distance (Markscheffel & Schröter, 2021). Both visualisations employ a two-dimensional distance-based map where the distance between two nodes reflects the relatedness of the respective keywords. A shorter distance indicates a stronger co-occurrence association, whereas a greater distance signifies a weaker relationship between the terms. A label and a circle, the size of which denotes the significance of the keyword, are used to identify it. The network visualisation depicts information about keyword cluster groupings, whereas the overlay visualisation illustrates the average annual publication of each keyword.

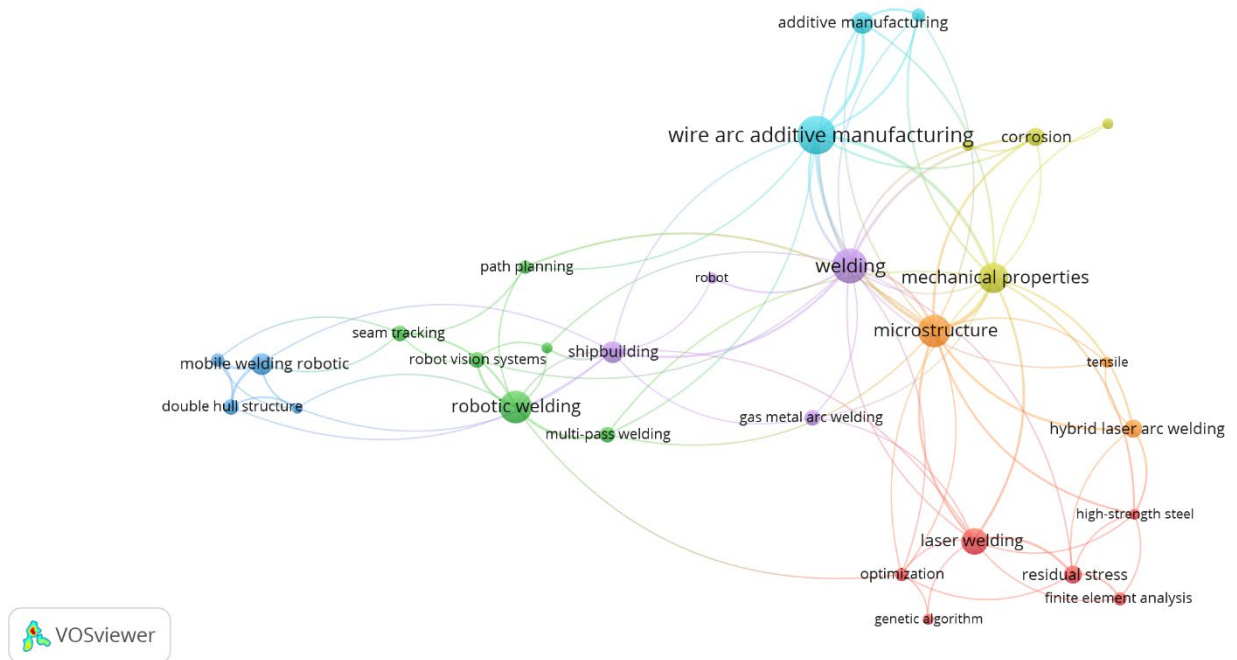


Figure 2-7 Network visualisation of keywords co-occurrence for robotic welding in marine applications.

The network visualisation of keywords can be seen in Figure 2-7 in which various clusters are formed. The item's colour is dictated by the cluster to which it belongs. The weight of an object determines the size of the label and the circle of the item. The greater the item's weight, the larger the item's label and circle. The inter-linked nodes show that keywords are used together in the study, while the lines weight illustrate the link strength between the keywords. It can be observed that wire arc additive manufacturing keyword is strongly linked with microstructure and mechanical properties. On the other hand, robotic welding itself is strongly linked with robot vision systems, multi-pass welding and seam tracking.

Figure 2-8 depicts the keywords relationship through overlay visualisation across the year. Links between nodes denote a cooperative or co-occurrence relationship. The coloured node indicates the publication year of the article carrying the keyword. It was discovered that the nodes of “corrosion”, “wire arc additive manufacturing”, “microstructure”, “mechanical properties”, “hybrid laser arc welding”, “path planning”, “finite element analysis” and “tensile” represented recent average publication time in past few years. Collectively, these keywords have been highly active and constitute prospective research opportunities.

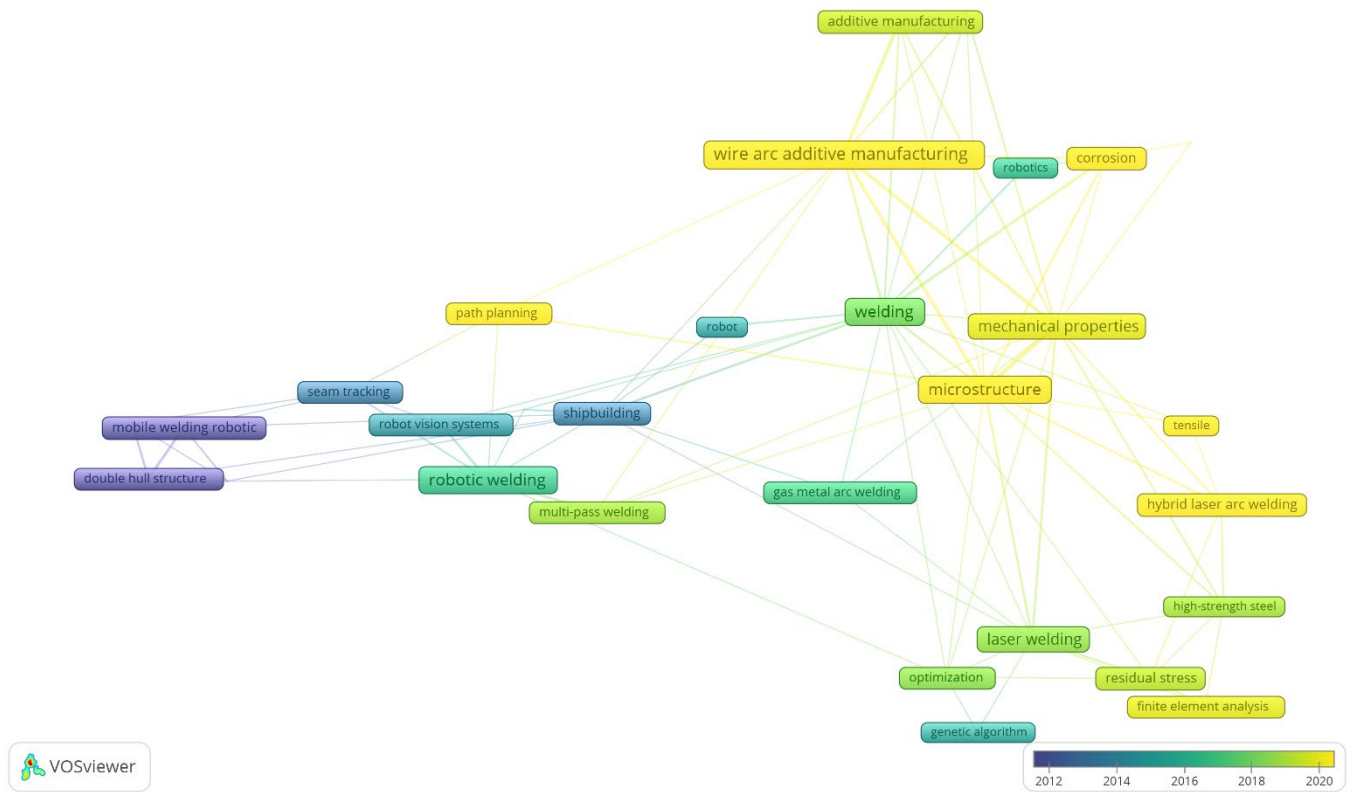


Figure 2-8 Keyword's overlay visualisation of co-occurrence for robotic welding in marine applications.

2.1.3.3 Types of robotic welding technologies and the processed materials

Figure 2-9 presents the evolution of the welding methods employed using robots from 2007 to 2022. Predominantly, gas metal arc welding (GMAW) played a pivotal role in the progression of robotic welding technology, as depicted in the blue chart. Between 2007 and 2013, only the GMAW method was featured in the documented studies, with a frequency of 1 to 4 papers annually. However, from 2014 to 2017, research began to diversify. In the field of marine structure and production, various welding techniques emerged, including friction stir welding, laser welding, stud welding, wire arc additive manufacturing, flux-cored arc welding, and hybrid laser arc

welding, each being the subject of at least one paper. Notably, from 2019 onwards, robotic welding studies focused on wire arc additive manufacturing surged in popularity, with the number of papers on this topic surpassing those on GMAW, culminating in a peak of 11 articles by 2022.

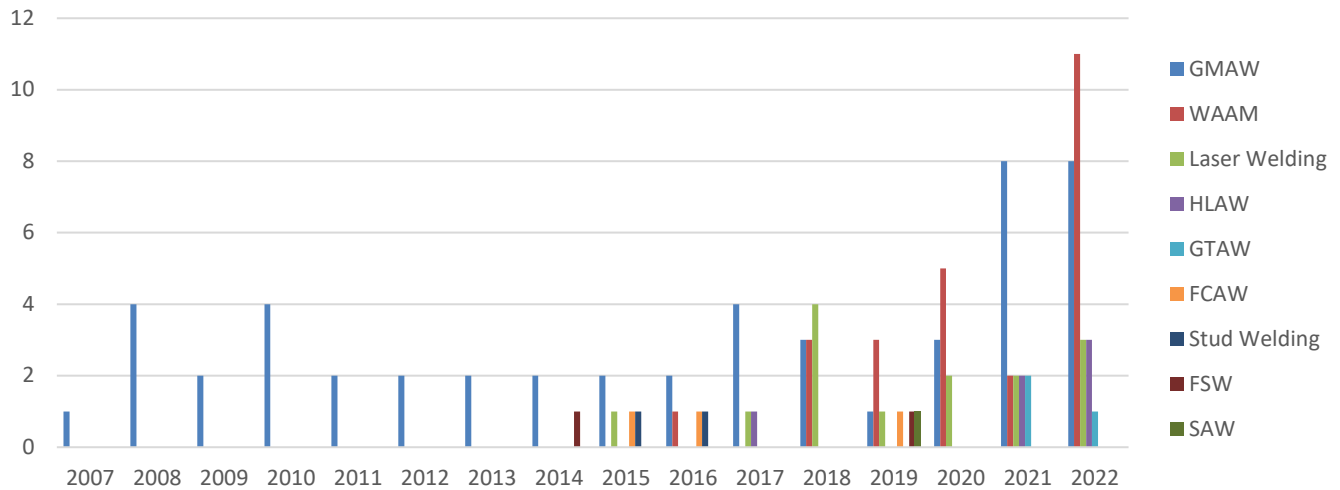


Figure 2-9 Robotic welding method in year distribution.

In the studies, carbon steel was the predominant processed material, as depicted in Figure 2-10. From 2007 to 2013, carbon steel was the sole material used in the reviewed studies, with the number of articles each year ranging from one to four. In the subsequent four years, materials such as aluminium, stainless steel, nickel-aluminium bronze, and high-strength steel began to be processed using robotic welding, each material being the subject of one paper. Starting in 2018, a broader range of materials were introduced to the realm of robotic welding. The studies started to feature advanced materials and alloys such as nickel-copper alloys, stainless steel, copper-aluminium alloy, super duplex stainless steel, high-Mn steel, nickel-chromium,

duplex stainless steel, and even titanium. These materials typically featured in one to two papers each year.

Regarding the application of robotic welding to various types of materials, Table 2-5 defines the welding methods employed in robotic welding technologies and showcases their utilisation across different materials. In general, the cited papers discuss nine robotic welding methods in marine applications, with gas metal arc welding, wire arc additive manufacturing, laser welding, and hybrid laser arc welding being the most frequently referenced. In comparison, flux-cored arc welding, gas tungsten arc welding, stud welding, friction stir welding, and submerged arc welding received less attention.

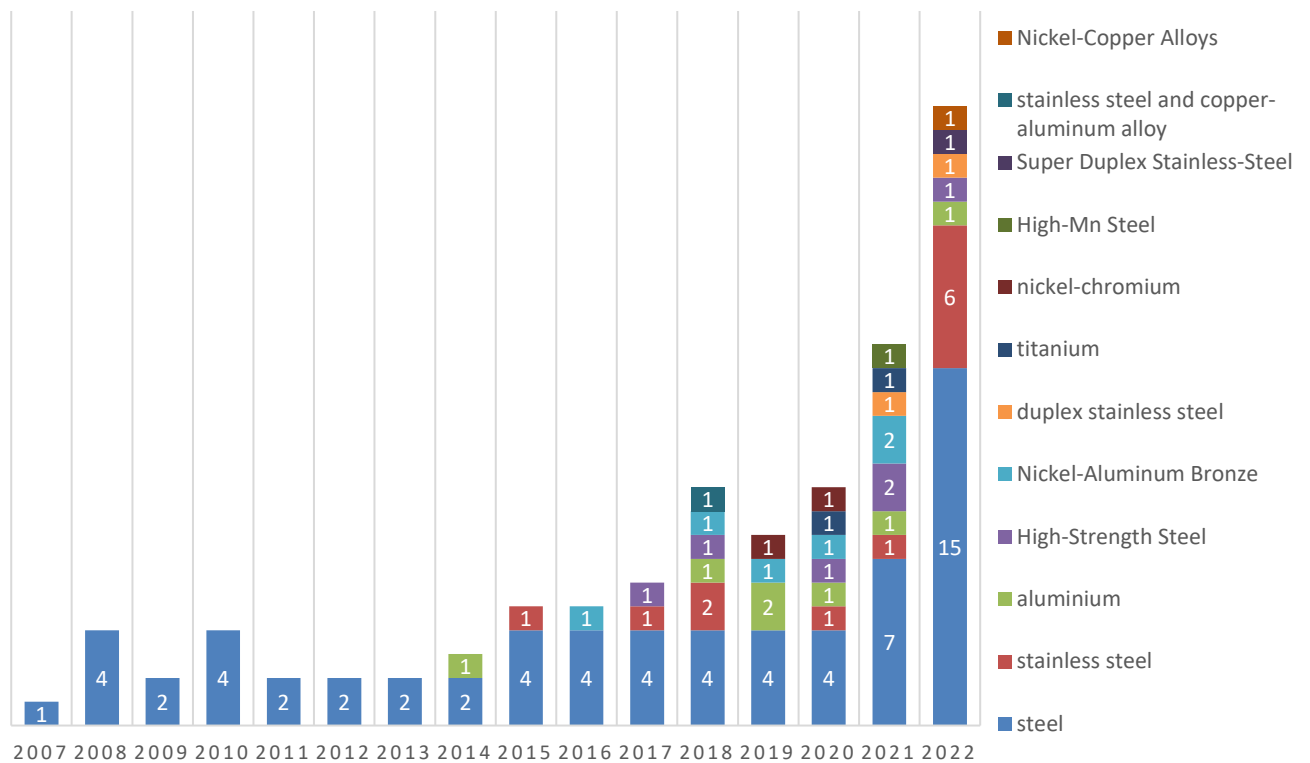


Figure 2-10 Yearly distribution of processed materials.

In terms of the distribution of robotic technologies across processed materials, as indicated in Table 2-5, gas metal arc welding primarily focused on steel, accounting for 39 articles, followed by stainless steel, high-strength steel, aluminium, nickel-aluminium bronze, and duplex stainless steel, totalling 11 articles. Steel, nickel-aluminium bronze, stainless steel, aluminium, nickel-chromium, super duplex stainless steel, duplex stainless steel, stainless steel-copper-aluminium alloy, and nickel-copper alloys were widely used in the context of wire arc additive manufacturing. However, steel remained the most frequently processed material for the other welding methods, followed by stainless steel, high-strength steel, high-MN steel, aluminium, and titanium.

Table 2-5 Types of robotic welding method and the processed materials

References	Robotic Welding Technology	Description	Processed Material	Article
(A. Ahmad, 2021; S. N. Ahmad et al., 2022; Ahmed et al., 2016; Cabral et al., 2015; Chang et al., 2012; X. Chen et al., 2018; Dharmawan et al., 2014; Epping & Zhang, 2018; Ferreira et al., 2017; F. Gao et al., 2015; B. Hong et al., 2021; Kang et al., 2008; M. Kazasidis et al., 2021; M. E. Kazasidis & Pantelis, 2017; J. Kim et al., 2008; K. Kim et al., 2010; T.-W. Kim et al., 2008; Le et al., 2017; D. Lee, 2013; D. Lee et al., 2010; D. Lee, Ku, et al., 2011; D. Lee, Seo, et al., 2011; K.-Y. Lee et al., 2008; Lezzi & Costa, 2013; Liao et al., 2022; S. Liu et al., 2022; W. Liu et al., 2022; Loukas et al., 2021; Mao et al., 2010; Morgado-Estevez et al., 2018; Oh et al., 2010; Papatheocharis et al., 2020; Park et al., 2009;	Gas Metal Arc Welding GMAW (50)	Referred to as MIG (Metal Inert Gas) welding or MAG (Metal Active Gas), is an arc welding process that uses a continuous solid wire electrode fed through a welding gun and into the weld pool. This process involves the use of an externally supplied shielding gas (commonly argon, carbon dioxide, or a mixture) that protects the molten weld pool from atmospheric contamination.	steel stainless steel high-strength steel aluminium nickel-aluminium bronze duplex stainless steel	39 4 3 2 1 1

References	Robotic Welding Technology	Description	Processed Material	Article
Pradhan et al., 2022; Pravin Kumar et al., 2022; Pravin Kumar & Siva Shanmugam, 2020; Romero-Hdz et al., 2016; Ryu et al., 2009; Sanders et al., 2012; Y. H. Shi et al., 2007; Srikanth et al., 2017; Tran et al., 2021; Woo & Kitamura, 2020; Q. Wu et al., 2021; Q. Q. Wu et al., 2014; Xia et al., 2021; Y. Zhang et al., 2019; Zheng, An, et al., 2022; Zheng, Xing, et al., 2022; Zhou et al., 2021)				
(Bekker & Verlinden, 2018; C. Chen et al., 2022; Dharmendra et al., 2019; D. Ding et al., 2016; Dörrle et al., 2022; Ermakova et al., 2022a, 2022b; Gufran et al., 2022; He et al., 2020; Jurić et al., 2019; Kannan et al., 2022; J. Kim et al., 2020; H. K. Lee et al., 2020; Long et al., 2022; Qi et al., 2022; Queguineur et al., 2018; Rajkumar et al., 2022; Ravi et al., 2020; Sales et al., 2022; Sales & Ricketts, 2019; Sasikumar et al., 2022; Shen et al., 2018; Świerczyńska & Landowski, 2020; Taşdemir & Nohut, 2020; Tianying et al., 2021)	Wire Arc Additive Manufacturing WAAM (25)	Additive manufacturing technique that employs an arc welding process to create metal parts. Using electric arcs as the heat source and wire as feedstock, layers of material are deposited successively to build up a three-dimensional object.	steel nickel-aluminium bronze stainless steel aluminium nickel-chromium super duplex stainless-steel duplex stainless steel stainless steel & copper-aluminium alloy nickel-copper alloys	8 5 4 2 2 1 1 1 1 1
(Ben et al., 2022; Kumar et al., 2017; Lai et al., 2020; Long et al., 2021; Pittner & Rethmeier, 2022; Rautio et al., 2019; Rong, Lei, et al., 2018; Rong, Mi, et al., 2018; Rong, Xu, et al., 2018; L. Wang et al., 2021, 2022; Xin et al., 2019; K. Zhang et al., 2018; P. Zhang et al., 2015)	Laser Welding (14)	A fusion welding technique that employs a laser as the heat source to melt and join materials together.	steel stainless steel titanium high-strength steel	8 3 2 1
(Hashemzadeh et al., 2022; D. S. Kim et al., 2021; G. F. Sun et al., 2017; Uemura et al., 2022; Yin et al., 2021; H. Zhang et al., 2022)	Hybrid Laser Arc Welding HLAW (6)	A method of fusion welding that combines the principles of arc and laser welding.	steel high-strength steel high-MN steel	3 2 1
(Oikonomou & Aggidis, 2019; Y. Wu et al., 2015; Xia et al., 2016)	Flux-Cored Arc Welding FCAW (3)	An arc welding process that employs a continuously fed tubular electrode containing a flux to produce the weld. This	steel	3

References	Robotic Welding Technology	Description	Processed Material	Article
		flux provides the necessary shielding from atmospheric contamination, which can sometimes be enhanced with additional external shielding gas.		
(Kershaw et al., 2021; Narenthiran et al., 2022; Vasilev et al., 2021)	Gas Tungsten Arc Welding GTAW (3)	Commonly known as Tungsten Inert Gas (TIG) welding, this particular arc welding technique employs a non-consumable tungsten electrode to generate the weld. In order to prevent atmospheric contamination, the weld region is protected through the use of an inert shielding gas, often argon or helium.	aluminium	1
			steel	1
			stainless steel	1
(Andersen et al., 2015, 2016)	Stud Welding (2)	A technique where a metal stud is joined to a metal workpiece without the use of a filler material. This process involves placing the stud in contact with the workpiece and igniting an arc. The heat from the arc melts the base of the stud and a portion of the workpiece, allowing them to fuse together. Upon solidification, a solid bond is created. Stud welding is often used for attaching fasteners, such as bolts or pins, to metal sheets in industries.	steel	2
(Gibson et al., 2014; Gurdal et al., 2019)	Friction Stir Welding FSW (2)	A solid-state joining process in which two workpieces are fused without melting the base materials. A rotating tool with a pin and shoulder is plunged into the interface of the workpieces and traversed along the joint. The frictional heat generated softens the material, allowing it to be stirred and bonded together.	aluminium	2
(Choudhary et al., 2019)	Submerged Arc Welding SAW (1)	An arc welding process that utilises a continuously fed consumable electrode to produce a weld. The arc and molten weld zone are submerged beneath a blanket of granular fusible flux, which protects the weld from atmospheric contamination	steel	1

References	Robotic Welding Technology	Description	Processed Material	Article
		and refines its properties. As the arc moves along the joint, the flux gets melted, and upon solidification, it forms a protective slag on the weld bead. SAW is known for its deep weld penetration, high deposition rates, and ability to produce sound welds, making it ideal for welding thick plates.		
Grand Total				106

2.1.3.4 Robotic welding types from the cited research experiments.

The cited articles cover a wide range of robotic welding processes used in various applications, including shipbuilding. These processes include TIG welding, ultrasonic-frequency pulse underwater wet welding, laser welding, wire arc additive manufacturing, gas metal arc welding, friction stir welding, and laser-MIG hybrid welding. These processes are used for joining different materials and have applications in marine structures, shipbuilding, and underwater environments. As shown in Table 2-6, some specific robotic welding systems used in the research experiments such as ABB, KUKA, Fanuc, Motorman, OTC Daihen, Panasonic, Rail Runner, Universal Robot, and Yaskawa are mentioned in 73 articles. These robot types are well-known in the field of industrial robotics and are likely to have developed 6-axis robotic welding systems that utilise the mentioned welding processes.

Table 2-6 Robotic welding types across the method used in the cited articles.

Type of Robot	FCAW	FSW	GMAW	GTAW	HLAW	Laser Weld	Stud Weld	WAAM	Grand Total
ABB (other type)			1			2		6	9
ABB IRB 140			1						1
ABB IRB 1410	1		1			1			3
ABB IRB 1520ID								1	1

Type of Robot	FCAW	FSW	GMAW	GTAW	HLAW	Laser Weld	Stud Weld	WAAM	Grand Total
ABB IRB 2400			1					1	2
ABB IRB 4400						1			1
ABB IRB 6660			1						1
Adaptive robotic control				1					1
Almega OTC AX V6								1	1
FANUC ARC M-100iC/12			1						1
FANUC M-10iA			1					1	2
FANUC M700i B45						1			1
Kawasaki (other type)			1						1
Kawasaki FA 06E			2						2
KUKA (other type)			1		2	3			6
KUKA KR 120						1			1
KUKA KR 16 arc HW								1	1
KUKA KR 16-2			3						3
KUKA KR 30 HA								2	2
KUKA KR 60 HA						2			2
KUKA KR3 R540			1						1
KUKA KR5 Arc HW				1					1
KUKA LWR 4+							2		2
Motorman HP20D								2	2
OTC Daihen (Other type)								1	1
OTC Daihen FD-B6			1					1	2
Other 6-axis industrial robot						1			1
Panasonic TA-1400								1	1
Prototype 6 axis robot			2						2
Prototype Robot			4						4
Rail Runner (RRX)			4						4
Rail Runner (RRX3)			3						3
Rail Runner (RRX4)			1						1
Rail Runner (RRXC)			1						1
Semi automatic robot			1						1
SP-MAG Panasonic			1						1
Stäubli TX200 robot		1							1
Universal Robot (UR16e)								1	1
YASKAWA HP20						1			1
Grand Total	1	1	33	2	2	13	2	19	73

The term "6-axis robotic welding" pertains to a welding technique that employs a robotic arm possessing six degrees of freedom for the execution of welding tasks, as depicted in Figure 2-11. The robotic arm is outfitted with a welding flame and possesses the capability to manoeuvre in various orientations, hence enabling the execution of intricate and accurate welding operations. The utilisation of this technology has garnered considerable interest across several industries, such as shipbuilding, owing to its capacity to enhance productivity, quality, and safety within welding procedures.

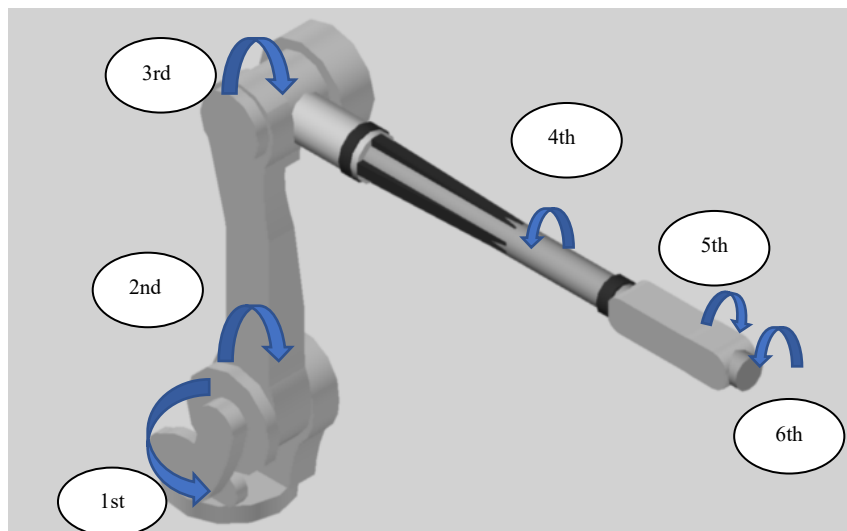


Figure 2-11 Six axes' movements of the robotic welding.

One of the primary benefits of 6-axis robotic welding is its capacity to execute welding tasks in hard-to-reach or tight regions. In shipbuilding, for example, where double-hulled constructions must be welded, a mobile robotic system with 6-axis capabilities has been created (Lee et al., 2010). This technique enables efficient and accurate welding in the confined gaps between a ship's inner and outer hulls.

In addition to its versatility, 6-axis robotic welding offers improved seam-tracking capabilities. Seam-tracking algorithms have been developed to detect characteristic points and track the welding path, ensuring accurate and consistent welds (Chang et al., 2012). These algorithms use sensors and vision systems to monitor the welding process and make adjustments in real-time, compensating for any deviations from the desired welding path.

Furthermore, 6-axis robotic welding can be integrated with other advanced technologies to enhance the welding process. For example, the use of digital twin-driven systems and offline programming methods can optimise the production line and improve the efficiency of the welding process (Q. Wu et al., 2021; Zheng, An, et al., 2022). Additionally, the integration of sensors and in-process ultrasonic non-destructive evaluation (NDE) systems enables real-time monitoring of the weld quality, ensuring that defects are detected and corrected during the welding process (Vasilev et al., 2021).

The choice of welding method and parameters is crucial in 6-axis robotic welding. Different welding methods, such as gas metal arc welding (GMAW), tungsten inert gas (TIG) welding, laser welding, and friction stir welding, have been applied in various applications (Choudhary et al., 2019; Gibson et al., 2014; D. S. Kim et al., 2021; S. Liu et al., 2022). The selection of the appropriate welding method depends on factors such as the material being welded, the desired weld quality, and the specific requirements of the application.

Moreover, the optimisation of welding parameters, such as welding speed, current, and shielding gas composition, plays a significant role in achieving high-

quality welds (Jurić et al., 2019; Narenthiran et al., 2022; Oikonomou & Aggidis, 2019). Advanced techniques, such as machine learning and genetic algorithms, have been employed to optimise welding speed and control parameters, ensuring optimal weld quality and reducing defects (X. Chen et al., 2018; Hashemzadeh et al., 2022; Kershaw et al., 2021).

2.1.3.5 Robotic welding categorisation and technological evolution

As presented in Figure 2-12, the classification of referenced robotic welding can be categorised into three main groups, which are determined by the mechanism used to manage the robotic systems. These categories include fully automated robots, remotely controlled robots, and robots operated by an onboard person. The category of fully automated robots operates without any human interference, while the category of remotely controlled robots includes systems that are controlled from a distance. Lastly, the category of onboard operator robots refers to those that are controlled by a human operator present on the robot itself (Saidi et al., 2016). The category of fully automated robots received the highest number of citations, with 68 articles accounting for around 64 percent of the total. In contrast, the categories of remote controlled and onboard operator robots were referred less frequently, with a total of 19 papers, or 18 percent of the citations.

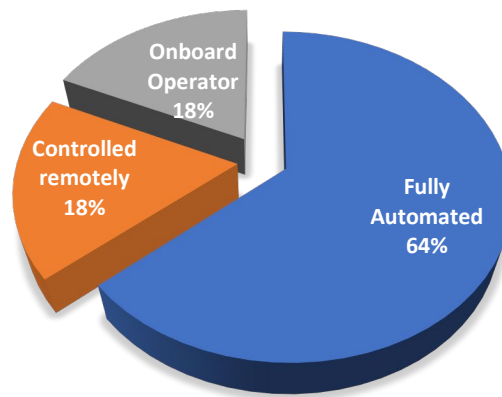


Figure 2-12 Classification of referenced robotic welding based on robotic system control mechanism.

The depiction of robotic welding categories across different time periods is elucidated in Figure 2-13. The visual trend portrays the evolution in the utilisation of distinct robot categories as observed in the analysed research papers. Initially, during the initial eight years, remote-controlled and onboard-controlled robots emerged as the prevailing choices. However, a noteworthy shift occurred in the subsequent eight years, as the fully automated robot category gained ascendancy.

Delving into the specifics, the application of remote-controlled and onboard-controlled robotic welding methods exhibited consistency throughout the entire timeline, with an annual publication rate of one to three papers. In contrast, the ascendancy of the fully automated category within the research sphere became evident starting from the year 2015. This category displayed an initially fluctuating pattern, marked by three to six annual publications until 2019. The subsequent years saw a remarkable surge in the use of fully automated robotic welding, asserting its dominance with 9, 14, and 25 papers in the final three years, respectively.

Fully automated robots have the capability to operate independently, devoid of any human intervention or assistance. The robots possess sensory capabilities and employ algorithms to comprehend their environment, make automated judgements, and perform tasks without human intervention. For example, Ahmed et al. (Ahmed et al., 2016) made an automated welding system for tubular joints that uses object detection and motion planning algorithms to do welding chores on its own.

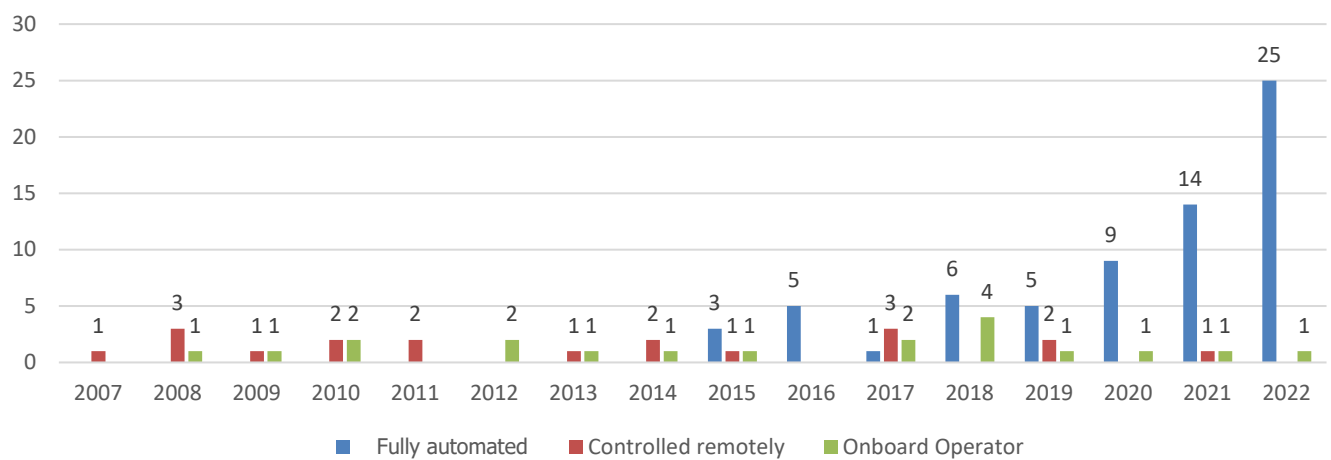


Figure 2-13 The categorisation of robotic welding across the years.

In contrast, remotely controlled robots are under the command of human operators who manipulate their motions and behaviours from a distant site. These robots are commonly outfitted with a variety of sensors and cameras that facilitate the acquisition of data, enabling the operator to make well-informed decisions and successfully manipulate the robot. In their study, Oh et al. (Oh et al., 2010) developed a teaching pendant software specifically tailored for a mobile shipbuilding welding robot. This program allows for remote control and monitoring of the robot's

movements and welding process through the utilisation of a Personal Digital Assistant (PDA).

The control of onboard operator robots is facilitated by an operator who is either physically situated on the robot itself or in close proximity to it. These robotic systems are frequently employed in scenarios that necessitate human involvement for jobs that cannot be entirely mechanised. For instance, a mathematical model was developed to describe the spatial configuration of the arc welding gun equipped with rotational arc sensors in a gas metal arc welding robot (Le et al., 2017). The technology allows for an aboard operator to effectively manage the robot's movements and carry out welding duties.

The robotic welding technologies mentioned can be classified into three distinct groups based on their state of development: implementing, developing, and prototyping (see Figure 2-14). The term "implementing category" pertains to technologies that have reached a state of full maturity and have been successfully employed in real-world construction projects. The developing category pertains to emerging technologies that, upon reaching a state of maturity, have the potential to significantly expand their applications within industrial projects. The prototyping group pertains to the ongoing development of robotic technologies, which are currently faced with various technological obstacles.

In general, the papers reviewed in this study predominantly utilised well-developed robotic welding techniques to conduct their research. Specifically, researchers in this field were engaged in prototyping and developing robotic welding technologies between 2007 and 2013, resulting in an annual output of one to three

papers. In contrast, post-2014 witnessed a substantial growth in the development of industrial robot welding, leading many researchers to gravitate towards this technology as a solution for a myriad of research challenges. From 2014 to 2017, a range of two to five articles were identified, all of which applied well-developed robotic welding methodologies within the research domain. Notably, within the last five years, this trend experienced a significant uptick, culminating in the publication of 26 papers in 2022. This surge unequivocally underscores the pervasive adoption of industrial robots, as all recorded papers exclusively employed these advanced robotic systems.

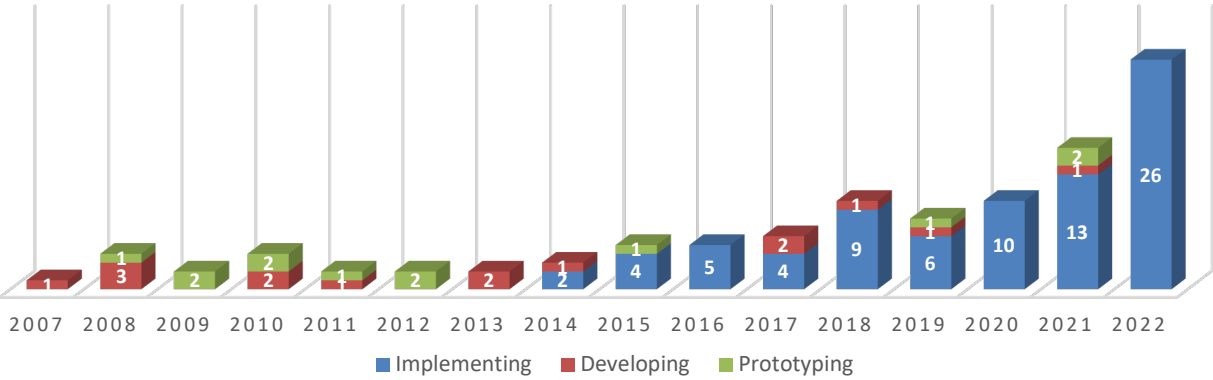


Figure 2-14 Level of development of robotic welding technology across the years.

2.1.3.6 Benefits and challenges in the robotic welding application

The utilisation of robotic welding has numerous advantages in terms of increased efficiency, improved quality, meeting industrial criteria, suitability for confined and hazardous environments, and enabling new construction techniques. As depicted in Figure 2-15, a significant proportion of the publications place emphasis on the advantages associated with the utilisation of robotic welding in order to boost efficiency, accounting for 39 percent of the total. A notable proportion of the

publications, specifically 26 percent, emphasise the potential of robotic welding in enhancing product quality. Subsequently, 20 percent of the papers focus on the subject of meeting industrial criteria. The papers highlight two additional advantages, namely the capacity to operate in confined and dangerous settings (9 percent) and the facilitation of new construction techniques (6 percent).

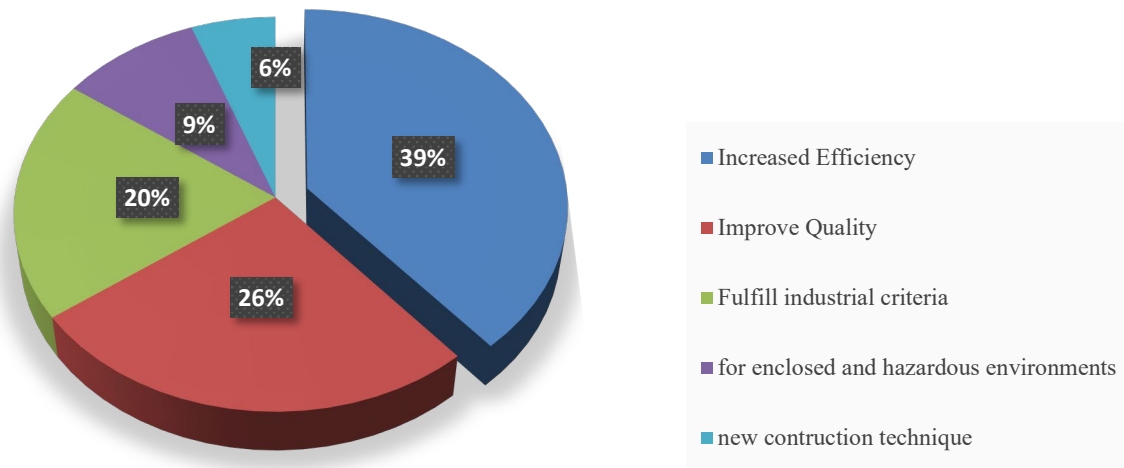


Figure 2-15 Advantages of robotic welding in marine applications.

Robotic welding offers significant advantages in terms of greater efficiency in marine applications. The use of robotic welding systems in shipbuilding and other marine industries allows for faster and more efficient welding processes (Kang et al., 2008). Robotic systems can work continuously without the need for breaks, resulting in increased productivity and reduced cycle times (Bekker & Verlinden, 2018). Additionally, they can be programmed to optimise welding parameters, such as travel speed and wire feed rate, to achieve the desired weld quality and efficiency (Choudhary et al., 2019).

In terms of quality improvement, robotic welding offers several advantages. The use of robotic systems eliminates human errors and inconsistencies, resulting in more consistent and reliable welds (L. Wang et al., 2021). Additionally, robotic welding enables the use of advanced welding techniques, such as laser welding and wire arc additive manufacturing (WAAM), which offer improved weld quality and performance (Kumar et al., 2017; Queguineur et al., 2018). Laser welding provides precise control and high-quality welds (Kumar et al., 2017). WAAM allows for the fabrication of complex geometries and customised components, reducing the need for manual welding and assembly (Queguineur et al., 2018).

Robotic welding is well-suited for enclosed and hazardous environments. The use of automation technology reduces the need for human operators to perform activities in hazardous situations such as tight spaces, hot environments, and poisonous substance locations (Chang et al., 2012; J. Kim et al., 2008; T.-W. Kim et al., 2008; Lee et al., 2010; Lee et al., 2011; Oh et al., 2010; Ryu et al., 2009). This method enhances safety and reduces the likelihood of incidents and injuries (K.-Y. Lee et al., 2008). Robotic welding systems can also be designed to withstand extreme temperatures and corrosive atmospheres, ensuring their dependability and endurance (Lee, 2013)(Chang et al., 2012).

The use of robotic welding in marine applications offers significant advantages in terms of fulfilling industrial criteria. Robotic welding systems can be designed and optimised to meet the specific requirements and standards of the marine industry (Sanders et al., 2012). They can be integrated into shipbuilding processes, providing precise and efficient welding solutions that adhere to industry regulations and

specifications (Lezzi & Costa, 2013). Welding joints manufactured under acceptable conditions meet Non-Destructive Testing (NDT) and mechanical test requirements as defined in standards (Uemura et al., 2022). Robotic welding systems can also be programmed, allowing for the generation of welding programs that meet the desired criteria and quality standards (Andersen et al., 2015). These techniques can meet the stringent requirements of marine applications, ensuring the durability and reliability of welded structures (Andersen et al., 2016).

Robotic welding enables the adoption of new construction techniques, such as arc welding and additive manufacturing, in certain marine structure components (C. Chen et al., 2022; Gufran et al., 2022; He et al., 2020; Papatheocharis et al., 2020; Tianying et al., 2021). Robotic welding systems can be used for wire arc additive manufacturing (WAAM), which involves depositing metal layers to build up a part (He et al., 2020; Tianying et al., 2021). Robotic welding systems can also be used for other advanced welding techniques, such as welding execution in underwater marine systems, which offer improved weld quality and performance (Oikonomou & Aggidis, 2019).

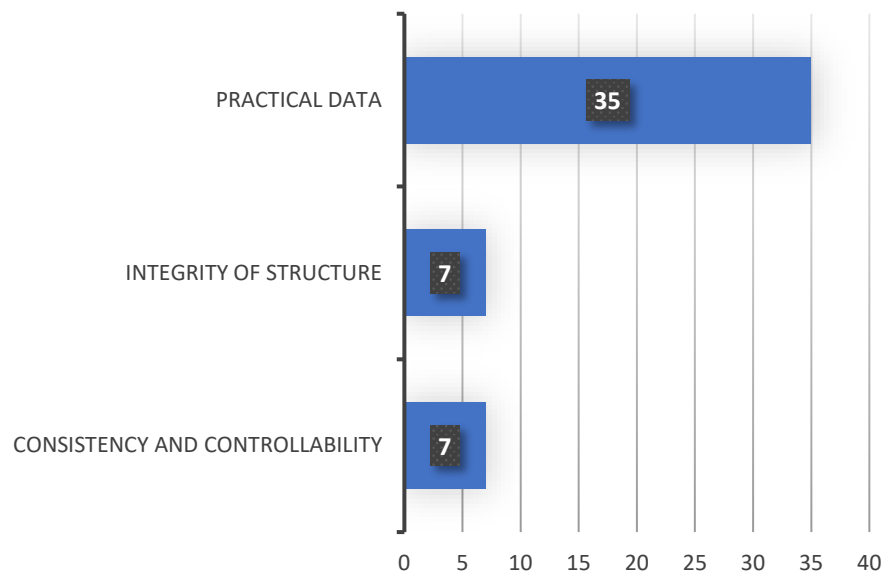


Figure 2-16 The challenges associated with the use of robotic welding in marine applications.

Despite the benefits, robotic welding in marine applications faces several challenges related to practical data, integrity of structure, also consistency and controllability reported in 49 articles, as shown in Figure 2-16. These challenges can impact the efficiency and effectiveness of the welding process, as well as the quality and reliability of the welded structures. The most cited challenge is the availability and accuracy of practical data for robotic welding (35 articles). Robotic welding systems require accurate information about the geometry and position of the workpiece to perform precise and consistent welds. The integrity of the welded structure is another critical challenge in robotic welding for marine applications (7 articles). The structural integrity and safety of marine vessels depend heavily on the strength and quality of the welds. The strength and quality of the welds can be influenced by elements including welding parameters, welding technique, and material qualities. To produce welds of sufficient strength and excellent quality, it is crucial to optimise the welding settings

and procedures. Consistency and controllability are also significant challenges in robotic welding for marine applications (7 articles). Consistent welding quality and performance are essential for ensuring the reliability and durability of welded structures. Robotic welding systems should be capable of maintaining consistent welding parameters, such as arc voltage, current, and travel speed, throughout the welding process. Advanced control algorithms and sensing techniques can be employed to achieve consistent and controllable welds.

2.1.4 Discussion

Robotic welding has gained significant attention in the marine industry for the production and construction of marine structures. The review includes a wide range of studies that cover various aspects of robotic welding, including different welding techniques, materials, categorisations, technological advancements, and the benefits and challenges in their application.

2.1.4.1 Robotic welding techniques and treated material types

Extensive investigations have explored the application of arc welding integrated with robotic systems to enhance marine structures and production processes such as GMAW, FCAW, GTAW, and SAW (S. N. Ahmad et al., 2022; Choudhary et al., 2019; Le et al., 2017; Vasilev et al., 2021; Xia et al., 2016). Additionally, numerous studies have investigated the utilisation of laser welding (Kumar et al., 2017; Rong, Mi, et al., 2018; K. Zhang et al., 2018; P. Zhang et al., 2015), with certain investigations using the integration of arc welding to form the Hybrid Laser-Arc Welding (HLAW) technique (Hashemzadeh et al., 2022; D. S. Kim et al., 2021; G. F. Sun et al., 2017; Uemura et al., 2022; Yin et al., 2021; H. Zhang et al., 2022). However, the integration

of wire arc additive manufacturing (WAAM) techniques with welding processes offers new possibilities for marine structures and production process. Additive manufacturing can be used to create complex and customised components, while welding is employed for joining and fabricating larger structures. The combination of these technologies enables efficient production and enhances design flexibility. Research by Taşdemir (Taşdemir & Nohut, 2020) demonstrated the integration of AM and welding for shipbuilding industry, showcasing the benefits of combining these processes. The integration of AM and welding facilitates rapid prototyping, reduces material waste, and opens up new design opportunities in marine applications.

The variability of materials and joint configurations in marine applications poses a challenge for robotic welding. The cited articles involve welding of various materials, such as steel (Rong, Mi, et al., 2018), aluminium (Sales & Ricketts, 2019), nickel-aluminium bronze (Dharmendra et al., 2019), stainless steel (Bekker & Verlinden, 2018), duplex stainless steel (Qi et al., 2022), titanium (Long et al., 2021), and nickel-cooper alloys (Kannan et al., 2022) with different properties and thermal conductivities. Joint designs and configurations may vary significantly, including butt joints (K. Zhang et al., 2018), fillet joints (Mao et al., 2010), tubular x-joints (Papatheocharis et al., 2020), and the welding position (e.g. horizontal and vertical-up) (Uemura et al., 2022). These variations require adaptability and flexibility in robotic welding systems to adjust welding parameters and techniques accordingly. Proper process development, parameter optimisation, and sensor-based control systems are necessary to address material and joint variability challenges.

Furthermore, the choice of materials and welding techniques can also influence the sustainability of robotic welding. The application of robotic welding in terms of energy efficiency and sustainability can be analysed through a life cycle assessment (LCA) approach. LCA is a systematic method used to evaluate the environmental impacts of a product or process throughout its entire life cycle, from raw material extraction to end-of-life disposal (Bekker & Verlinden, 2018; Pittner & Rethmeier, 2022). In the context of robotic welding, LCA can provide insights into the energy consumption, greenhouse gas emissions, and other environmental impacts associated with the manufacturing and operation of robotic welding systems.

2.1.4.2 Categorisation of robotic welding and technological advancements

According to robotic welding categorisation, each category of robotic control mechanism has its advantages and limitations. Fully automated robots offer the potential for increased efficiency and productivity as they can operate continuously without human fatigue or limitations (Zheng, An, et al., 2022). However, they require sophisticated sensing and decision-making capabilities, as well as robust algorithms to ensure safe and accurate operation (Chang et al., 2012). Remotely controlled robots provide the flexibility of human decision-making and intervention, allowing for adaptability to changing conditions and complex tasks (Lee, 2013). Onboard operator robots offer the advantage of direct human control and physical presence, which can be beneficial for tasks that require dexterity and fine motor skills (Mao et al., 2010). The choice of control mechanism depends on the specific requirements of the task and the desired level of human intervention. Further research and development in these

areas can lead to advancements in robotic systems and their applications in various industries, including shipbuilding, welding, and manufacturing.

Regarding technological evolution, robotic welding plays a crucial role in research, encompassing various stages from prototyping to technology development and industrial implementation. In the prototyping stage, researchers focus on designing the automatic robotic welding process and introducing advanced algorithms and sensors. Sanders et al. (Sanders et al., 2012) introduced a corner-finding algorithm to help recognise shipbuilding parts, improving the automatic robotic welding process in shipbuilding. Park et al. (Park et al., 2009) developed a precise 3D lug pose detection sensor using a structured-light vision system for automatic robot welding, contributing to the accuracy and efficiency of robotic welding systems. Kang et al. (Kang et al., 2008) developed a multi-welding robot system for sub-assembly in shipbuilding, demonstrating the practical implementation of robotic welding in the shipbuilding industry.

Developing the technology involves improving and optimising the platform for portable robotic welding in large-scale structures. Dharmawan et al. (Dharmawan et al., 2014) conducted a survey of platform designs for portable robotic welding in large-scale structures, exploring different design considerations and proposing solutions to improve the portability and flexibility of robotic welding systems. Lee et al. (Lee et al., 2011) optimised a mobile welding robot by through examination of its workspace utilising a 3P3R serial manipulator.

Implementing robotic welding in industrial settings requires addressing specific challenges and optimising the welding process. For example, Kumar et al. (Kumar et

al., 2017) conducted a comparative study of pulsed Nd: YAG laser welding of AISI 304 and AISI 316 stainless steels, providing insights into the welding parameters and material composition for optimal weld quality. Furthermore, the use of advanced technologies such as laser penetration welding and wire arc additive manufacturing (WAAM) has been explored in shipbuilding. Rong et al. (Rong, Mi, et al., 2018) investigated laser penetration welding of ship steel EH36 and its application in predicting residual stress. Bekker & Verlinden (Bekker & Verlinden, 2018) conducted a life cycle assessment of wire + arc additive manufacturing compared to other manufacturing processes in stainless steel, highlighting the environmental benefits of this technology.

2.1.4.3 Applications of robotic welding: advantages and challenges

Robotic welding offers several benefits in terms of efficiency, improved quality, meeting industrial criteria, suitability for confined and hazardous environments, and enabling new construction techniques. These advantages make robotic welding a valuable tool in various industries, including shipbuilding, manufacturing, and construction. However, robotic welding in marine applications faces challenges related to practical data, integrity of structure, consistency, and controllability. These challenges can be addressed through the use of advanced technologies, such as object detection and motion planning, laser vision sensing, optimisation of welding parameters, and adaptive control algorithms. Yet, high initial investment and maintenance costs are significant barriers to the adoption of these technologies, especially for small and medium enterprises (Epping & Zhang, 2018). Therefore, cost-effective solutions and governmental support could be vital in facilitating the

widespread use of robotic welding in the marine industry. Future research should focus on developing cost-effective, reliable, and durable robotic welding systems, especially for marine structures and production processes.

The use of 6-axis robotic welding in shipbuilding and other industries offers numerous benefits, including increased productivity, improved welding quality, and enhanced worker safety. However, challenges such as the need for accurate path planning, control of heat input, and mitigation of residual stresses and deformations still need to be addressed (D. Ding et al., 2016; Romero-Hdz et al., 2016; Rong, Lei, et al., 2018). In addition, its ability to perform complex welding tasks, reach difficult-to-access areas, and integrate with advanced technologies makes it a valuable tool for improving productivity and weld quality. Future research and development efforts can be addressing these challenges and further improving the capabilities and performance of 6-axis robotic welding systems.

Addressing these challenges and limitations in implementing robotic welding in marine applications requires a comprehensive approach that includes technological advancements, careful cost analysis, skill development, and effective process planning. Overcoming these hurdles will enable shipbuilders to harness the full potential of robotic welding and optimise marine structures and production processes.

2.2 Critical Review of Robotic Welding in Structural Optimisation

This sub-chapter provides a critical review that systematically analyses the intersection between robotic welding capabilities and contemporary ship structural optimisation methodologies. While conventional optimisation models predominantly focus on reducing hull weight by altering plate thicknesses and increasing stiffener

density, they frequently neglect the physical and kinematic constraints of automated manufacturing. This section evaluates how such weight-centric design choices inadvertently restrict robotic accessibility, introduce high collision risks, and create localised spatial traps within enclosed marine structures. By critically examining these technical bottlenecks, this review establishes the necessary engineering justification for shifting toward an integrated, robot-informed optimisation framework that concurrently balances structural efficiency with automated production feasibility.

2.2.1 Using Welding Robots to Optimise Production Processes and Costs

In modern industry, robots have become widely used in factories, where they have taken over many tasks that were once performed by humans. For example, robots have become the prime movers in the automotive, electronic device, and computer device industries. Robots are used because they are accurate, efficient, and cost-effective. Robots can perform tasks quickly and accurately, and they can do so without getting tired or making mistakes. This can help to improve productivity and save money. In an effort to expand manufacturing capacity, researchers have been studying automated (robot-based) production (Lee et al., 2011). This research has led to the development of new technologies, such as innovative product design using topology optimisation and additive manufacturing (Primo et al., 2017), a transportable robotic system for ship structures (Lee et al., 2010), and an intelligent inspection robot for dangerous and inaccessible sites (Rea & Ottaviano, 2018). Robotic automation has become increasingly common in the Japanese shipbuilding industry, in response to changes such as a decrease in the labour force and wage hikes. This is especially true for arc welding (Okumoto, 1997). Some research has been conducted on the use of

robots in welding applications. For example, one study found that welding process variables affect the quality of robotic MIG welding of EN24T steel (Ali et al., 2022). Another study developed a robotic seam-tracking system using conditional generative adversarial networks and laser vision (CGAN) (C. Liu et al., 2022). Other study of robot welding application was of a robot-assisted MIG/MAG welding system called “MyWelder” which was proposed as an excellent productive, intuitive, and easily customisable technology (Ferraguti et al., 2023). In addition, research has been conducted on the design of fully automated fabrication facilities for the shipbuilding sector. One study provided a layout for an automated fabrication workshop (J. G. Shin & Sohn, 2000). The workshop includes work areas for cutting, rolling, line heating, and loading of products, as well as for registering material plates. Therefore, it is important to analyse the current state of robotic welding technology in ship production technology.

The shipbuilding industry plays a pivotal role in constructing vessels that navigate our seas, and welding is a critical process within this industry. Welding is essential for joining structural components, ensuring the integrity and strength of the ships. The shipbuilding industry faces challenges in achieving efficient and high-quality welding processes. Conventional welding techniques are labour-intensive, prone to human error, and may have limitations in terms of productivity and quality control. On the other hand, robotic welding offers potential solutions by leveraging automation, precision, and consistency in the welding process. Robotic welding systems have the capability to improve productivity, reduce labour costs (Wahidi, Pribadi, Pribadi, Wardhana, et al., 2021), and enhance weld quality in shipbuilding

applications. However, implementing robotic welding in shipbuilding requires addressing challenges related to the initial investment, programming, flexibility, and maintenance. Addressing these challenges is crucial for enhancing efficiency, weld quality, and cost effectiveness in the shipbuilding industry (Lezzi & Costa, 2013).

The technical and economic aspects of shipbuilding are increasingly intertwined, with the optimisation of the production process and reduction in costs being critical factors in maintaining competitiveness in the industry (Arif et al., 2022; Koenig, 2002; Pribadi et al., 2021; Pribadi & Shinoda, 2022; Rubeša et al., 2023; Wahidi, Virmansyah, et al., 2021). A large amount of research has been conducted on the use of robotic welding technology in the manufacturing industry. Some of the most notable studies include those by Zhang et al. (Q. Zhang et al., 2023), Feng et al. (Feng, Gao, et al., 2020), Chen (S. B. Chen, 2007), Shapovalov et al. (Shapovalov et al., 2016), and Jr et al. (Jr et al., 2000). Other studies have focused on the use of robot welding in shipyards. For example, Feng et al. (Feng, Tian, et al., 2020), Rooks (Rooks, 1997), Kim et al. (D. S. Kim et al., 2021), and Olschok et al. (Olschok et al., 2018) have all published research on this topic. However, there is a notable scarcity of literature providing a direct, detailed comparison between robotic and conventional manual welding in terms of both technical execution and economic performance specifically applied to ship block assembly in confined double-bottom structures. This study initially evaluates and compares the performance of robotic welding against conventional manual methods within the context of complex maritime assembly, focusing specifically on enclosed double-bottom structures as detailed in Chapter 4.

This is undertaken by applying the optimal means of assembling complex ship structures (Lee et al., 2011).

2.2.2 Optimisation Frameworks for Stiffened Panels in Restricted Environments

The global shipbuilding industry is continuously motivated by the necessity to decrease vessel weight, thus lowering fuel consumption and contributing to the reduction of CO₂ emissions (Yan et al., 2020). Reducing ship weight is a primary objective for designers and owners, as it directly leads to less fuel consumption (Elhewy et al., 2016). An essential component of ship construction is the assembling of stiffened plates, which form a substantial part of the vessel's structure, encompassing the deck, bottom, and side parts (Aydin et al., 2020). The double bottom, an essential structural element, is notably difficult to produce because of its frequently confined spaces, resulting in more time-consuming and costly manufacturing methods than those for single-hulled vessels (Lee, 2013). The requirement for significant welding intensifies the complexity, thereby increasing material handling and overall production expenses.

Structural optimisation is a key strategy for achieving efficient, safe, and cost-effective vessel construction (Aydin et al., 2020). A primary goal is to reduce the overall structural weight (Caprace et al., 2010), which contributes to improved fuel efficiency, increased payload capacity, and reduced environmental impact (Mandal, 2017). Early studies primarily concentrated on reducing the thickness of base plates and increasing the number of stiffeners (Putra et al., 2019). While effective in lowering weight, such methods often introduce new challenges, including increased fabrication

complexity, longer production times, and higher costs especially when non-standard stiffener types are introduced (Sekulski, 2009).

The ship's double bottom is constructed by assembling individual components into panels and blocks before forming the complete structure (Eyres & Bruce, 2012), using a process similar to that of constructing other floating structures such as floating docks (Wahidi et al., 2022). Figure 2-17 illustrates the production steps for creating a closed block, a sub-module of a double-bottom ship (Wahidi et al., 2023). The process begins with the separate assembly of a bottom shell and an open block through welding. The bottom shell consists of a broad steel plate reinforced with several parallel longitudinal stiffeners. The open block, which is more intricate, starts with the fabrication of a bottom plate mirroring the top plate's shape. Next, transverse web floors and girders are attached to the inner bottom plate. In the following phase, pre-fabricated unit panels, each with longitudinal stiffeners, are accurately positioned on the open block (Lee et al., 2011). These panels are then welded to the open block along the stiffeners to ensure a strong connection. The welding process, currently performed by human workers, is one of the most difficult and hazardous jobs in the shipbuilding industry due to the severe environmental conditions, including temperatures of 40–50°C in the summer, darkness, and considerable amounts of metallic dust, fumes, and gases produced by welding (Lee et al., 2010).

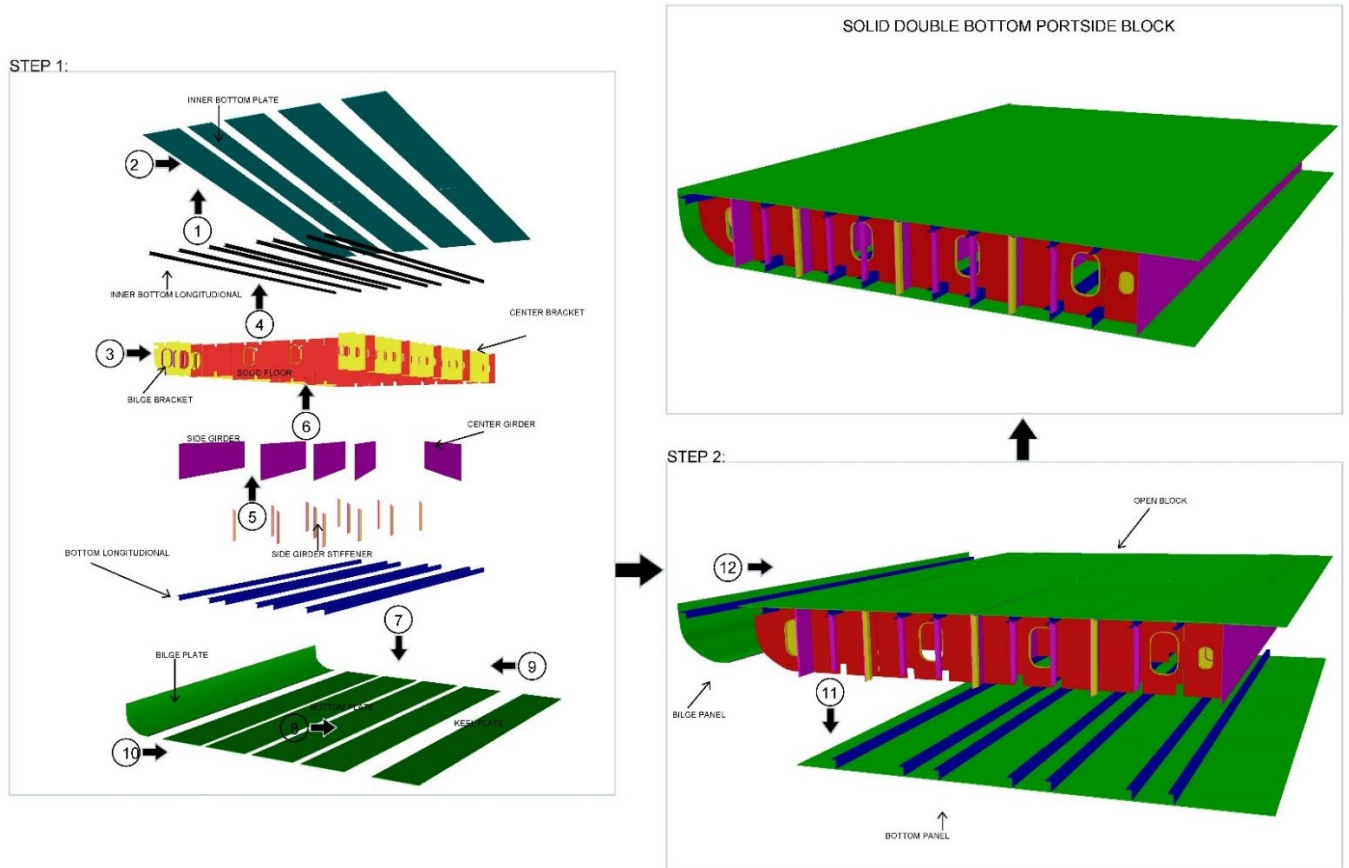


Figure 2-17 Double-Bottom Construction Process in Shipbuilding (Wahidi et al., 2023)

Additionally, welding operations in confined shipbuilding spaces, such as within hull blocks or narrow compartments, pose significant safety risks and can lead to project delays (Wahidi et al., 2023). These environments are difficult to access, increasing the likelihood of welding defects and worker fatigue (Mandal, 2017), and complicating quality control (Arif et al., 2022). The combination of increased welding requirements and restricted working conditions can significantly impact both safety and production efficiency (Lee et al., 2011).

Research has been conducted on developing robotic welding for working in confined spaces, with several studies having been published (Lee, 2013). However,

there are still significant challenges and limitations that need to be addressed to fully exploit the potential of robotic welding in the marine industry, especially when dealing with complex structures (Wahidi et al., 2024). To address these challenges, this research demonstrates a structural optimisation approach that simultaneously targets weight reduction and the minimisation of welding operations, particularly in confined spaces (Wahidi et al., 2023). Unlike conventional methods that tend to increase the number of stiffeners (Putra et al., 2019), this study maintains a constant stiffener count while optimising their dimensions and the thickness of associated plates. This approach ensures that the welding workload does not increase, thereby improving safety and reducing production costs (Dharmawan et al., 2014).

Recent advancements in computational optimisation techniques, such as genetic algorithms (Cai & Jelovica, 2022), topology optimisation (Kendibilir & Kefal, 2023), and response surface methodologies (Lee et al., 2015), have enabled more sophisticated approaches to structural design (Guerra et al., 2024). These methods allow for multi-objective optimisation (Ehlers et al., 2015), balancing weight reduction with other critical factors such as structural integrity, manufacturability, and reliability (Yu et al., 2024). In particular, multi-objective genetic algorithms (MOGAs) have been widely adopted due to their ability to handle complex, nonlinear design spaces and conflicting objectives (Alexakis et al., 2025).

However, many optimisation studies have overlooked the practical implications of increased welding requirements, especially in confined spaces. Welding in such environments poses significant safety risks, including exposure to fumes, limited mobility, and increased fatigue for workers (Wahidi et al., 2022). Moreover, the

complexity of welding operations in restricted areas can lead to delays in project timelines and higher labour costs (Pribadi et al., 2025).

Some researchers have begun to address these concerns by incorporating manufacturability constraints into the optimisation process. For example, studies have explored the impact of stiffener layout and accessibility on welding efficiency and safety (Sekulski, 2010). Others have proposed design-for-assembly frameworks that consider verification rules including heeling moment, interference inspection and escape time during the early stages of structural design (Wang et al., 2024).

Despite these advancements, there remains a gap in the literature regarding integrated approaches that simultaneously minimise structural weight and welding effort, particularly in the context of confined shipbuilding spaces. This research also aims to fill that gap by proposing a structural optimisation framework that maintains a constant number of stiffeners thus avoiding additional welding while optimising their dimensions and plate thickness. The goal is to achieve a lighter structure without compromising safety or increasing production costs which is detailed in Chapter 5.

The optimisation framework discussed in Chapter 5 is based on a multi-objective genetic algorithm (MOGA) integrated with response surface methodology and constraint rules classification. This combination enables efficient exploration of the design space while ensuring compliance with structural integrity and fabrication constraints (Wahidi et al., 2024). The study focuses on stiffened panel structures commonly used in ship block construction, demonstrating how targeted optimisation can lead to practical improvements in both design and production.

2.2.3 Robotic Reachability Boundaries as Structural Design Constraints

The global shipbuilding industry operates within a highly competitive landscape, where demands for rapid construction cycles, guaranteed structural quality, and adherence to stringent safety regulations are paramount (Rose & Coenen, 2016). As a critical sector for international trade and defence, the pursuit of enhanced production efficiency is an ongoing imperative (Lee et al., 2011). The fabrication of large commercial vessels and naval ships relies heavily on welding (J. G. Shin & Sohn, 2000), which often constitutes the most time-consuming and cost-intensive phase of the construction process (Dharmawan et al., 2014).

Key manufacturing tasks in shipyards, especially those carried out in geometrically constrained environments, still heavily rely on manual labour despite extensive advancements in industrial automation (Gharbia et al., 2020). One such crucial but difficult area is the double-bottom portion of a ship hull (Seong et al., 2013), which is distinguished by its intricate internal stiffeners, webs, and frames (Wahidi et al., 2023). Manual welding in these small areas, which are frequently marked by poor visibility and challenging access, presents serious operational and logistical challenges (Wahidi et al., 2022). These difficulties include increased ergonomic strain, significant weld quality variability, inherent worker safety risks, and longer production cycles as a result of required repositioning and constrained throughput. This logistical bottleneck undermines the financial sustainability of contemporary shipbuilding programs (Pribadi et al., 2025) by seriously impeding overall shipyard productivity and causing project delays (Semini et al., 2023).

The maritime sector is presently going through a major transition toward "Shipbuilding 4.0," where worker safety and production efficiency are increasingly dependent on robotic automation (Muhuri et al., 2019). Welding the double-bottom structure remains among the most hazardous and labour-demanding operations in modern shipyards. Under international classification standards, double-bottom heights typically range from statutory minimums of 0.76–1.0 m in small commercial craft up to over 2.0 m in large container vessels. In medium-sized cargo ships and product tankers (such as the 7,700 DWT vessel evaluated in this study), this vertical clearance is frequently restricted to 1.1–1.2 m, presenting severe accessibility bottlenecks and ergonomic hazards for human welders (Pribadi & Shinoda, 2025). As a result, using robotic welding systems in these settings is now a requirement for contemporary shipyards rather than a choice.

Previous research has explored the application of robotics and simulation in large-scale assembly and open panel welding (Lee et al., 2010). However, a crucial gap remains in the validated application of readily available, market-standard robotic welding systems to the intensely confined and kinematically demanding geometries of areas like the double-bottom structure. Specifically, there is a lack of rigorous, simulation-based studies that unequivocally prove the manufacturability of confined structural designs using existing robotic technology. The industry needs assurances that structural optimisations (Klanac et al., 2009), intended to improve vessel performance, do not inadvertently introduce unmanageable kinematic limitations for automated systems (Queguineur et al., 2018).

The transition to automated welding in such restricted geometries is plagued by kinematic limitations (Wahidi et al., 2024). Most industrial robots are designed for open-floor manufacturing, and their application within a ship's cellular structure often leads to frequent collisions and unreachable weld targets (Mourtzis et al., 2019). Previous studies have explored various robotic configurations, but few have addressed the specific kinematic interference occurring when robots must move transversally across multiple bays in a 1.2-meter height constraint.

While floor-mounted robots offer high stability, their inability to easily transition between stiffener-bounded compartments limits their overall duty cycle. Conversely, mounting robots directly on stiffeners facilitates better transversal mobility but introduces a high risk of "Axis 3" collisions with the overhead structure. This research utilises a Virtual Prototyping Framework (VPF) to evaluate these mounting strategies through high-fidelity simulations in ABB RobotStudio which is detailed in Chapter 6.

2.2.4 Integration of Robotic Manufacturing Constraints into Multi-Objective Optimisation

The maritime industry is currently undergoing a significant transformation towards smart manufacturing shipyard (Moghaddam et al., 2018), where automation and robotic integration are pivotal to enhancing productivity and safety (Wahidi et al., 2024). One of the most critical and labour-intensive processes in ship construction is the welding of double bottom blocks (Eyres & Bruce, 2012). These structures, characterised by complex networks of longitudinal stiffeners, floors, and girders, present a highly challenging environment for human welders due to the confined space and poor ergonomic conditions (Okumus et al., 2023).

Incorporating sophisticated automation into ship block assembly substantially boosts manufacturing output by streamlining intricate welding tasks throughout various production phases (Lee, 2014). In the early 'open block' stage (Kang et al., 2008), a specialised robotic welding gantry is typically utilised to achieve high-precision joins on accessible structural members (Morgado-Estevez et al., 2018). However, once the assembly is inverted and secured to the bottom shell, forming a 'closed block' configuration (see Figure 1-1), the accessibility for automation shifts. This stage demands the use of mobile robotic systems designed to navigate within enclosed volumes to perform essential internal welding (Lee, 2013). A critical task in these restricted compartments is the execution of 'U-shaped' weld paths, which integrate longitudinal stiffeners with the bottom floors (Lee et al., 2011). This automated sequence is vital for maintaining structural robustness in areas where conventional manual welding is hindered by severe spatial constraints (Jia et al., 2025).

Despite the clear advantages of robotic welding in improving weld quality and reducing production cycles, its implementation in double bottom blocks remains obstructed by design-related barriers. Traditionally, ship structural optimisation has been driven primarily by weight minimisation and structural integrity, governed by classification society rules (Lima et al., 2025). While effective, traditional design methodologies often introduce unintended complications (Putra et al., 2019), including heightened manufacturing complexity and extended production timelines. These issues frequently lead to escalated labour costs (Pribadi et al., 2025), especially in cases where non-standard stiffener configurations are implemented to meet structural requirements (Wahidi et al., 2025). Furthermore, conventional structural optimisation

typically focuses solely on weight reduction (Sekulski, 2009), often resulting in an increased number of smaller stiffeners. While this may reduce mass, it inadvertently increases the total length of weld joints, thereby complicating the assembly process and extending the robotic welding cycle (Pradhan et al., 2022). These "weight-centric" designs often result in scantlings that are structurally sound but manufacture-impenetrable, leaving insufficient clearance for robotic manipulators to navigate and perform precise welding tasks (S. Liu et al., 2024).

Recent studies in multi-objective structural optimisation (MOSO) (J. Wu et al., 2017) have utilised advanced meta-modelling techniques, such as Response Surface Methodology (RSM) (Cong et al., 2025) and Genetic Algorithms (Y. Ding et al., 2026), to balance conflicting objectives like mass reduction and stress distribution. Nevertheless, a significant research gap persists: the exclusion of robotic kinematic constraints during the early structural design phase. Most optimisation frameworks treat manufacturing accessibility as an afterthought, leading to costly design revisions or the necessity for expensive, custom-made robotic solutions.

Chapter 3. Procedure and Methodology

This research employs a multi-disciplinary approach combining naval architecture, robotic kinematics, and computational optimisation. The methodology is structured into five distinct phases to bridge the gap between ship structural design and automated manufacturing feasibility. The overall workflow transition from theoretical identification to virtual validation, and finally to the synthesis of an integrated optimisation framework. Details of the framework can be seen in Figure 3-1.

3.1 Problem Identification and Systematic Review

The initial phase focuses on mapping the current landscape of robotic applications in shipbuilding (Wahidi et al., 2024). A Systematic Literature Review (SLR) (Page et al., 2021) was conducted to systematically map the landscape of automation in shipbuilding and address the core research questions. Every selected literature study was rigorously analysed and categorised based on five critical dimensions of inquiry:

a. Technical Taxonomy: Classification of Robotic Welding Methods

The extraction process begins by identifying the specific welding methods integrated with robotic technology across the collected literature. Studies are classified based on the arc welding variants and heat source characteristics utilised, such as:

- ✓ Flux-Cored Arc Welding (FCAW)
- ✓ Gas Metal Arc Welding (GMAW / MIG / MAG)

- ✓ Wire Arc Additive Manufacturing (WAAM)
- ✓ Tungsten Inert Gas (TIG) and Laser-Arc Hybrid variants.

Mapping these methods allows the review to establish which thermal processes are most adaptable to automated configurations in marine engineering.

b. Hardware & Architecture Evaluation: Types of Robotic Systems

The methodology evaluates the physical and kinematic architecture of the robotic welding systems employed in the research experiments. Literature data is extracted and clustered into distinct hardware typologies, including:

- ✓ Standard 6-axis industrial manipulators (e.g., articulated track-mounted or fixed-base robots).
- ✓ Portable and compact welding gantry systems.
- ✓ Mobile autonomous or semi-autonomous trackless magnetic crawlers engineered specifically for double-hull and internal block compartments.

This classification identifies the structural reachability limits and spatial adaptability of existing hardware designs.

c. Material Process Analysis: Metallurgical Scope

To understand the operational boundaries of the automated systems, the review extracts specific data regarding the materials processed during the reported experiments. The literature is segmented based on the metallurgical properties and thickness profiles of the marine-grade materials utilised, predominantly focusing on:

- ✓ High-tensile shipbuilding steel (e.g., AH32, DH36, EH36 grades).
- ✓ Duplex stainless steels and anti-corrosive alloys.
- ✓ Aluminium alloys utilised in high-speed marine craft.

This dimension correlates the mechanical performance of the automated weld with its metallurgical constraints.

d. Impact Assessment: Synthesis of Potential Advantages

The methodology systematically synthesises the quantifiable advantages derived from implementing robotic systems over conventional manual welding. The review extracts performance indicators from empirical papers and clusters them into three key impact domains:

- ✓ Production Efficiency: Increases in travel speed, cycle time reductions, and arc-on time optimisation.
- ✓ Quality Consistency: Reductions in weld defects (porosity, distortion) and structural rework.
- ✓ Economic and Ergonomic Value: Labor cost minimisation (Wahidi et al., 2021), energy-efficiency ratios, and the reduction of human welder exposure to toxic fumes in hazardous, confined zones.

e. Gap Analysis: Industrial Obstacles and Deficiencies

A comprehensive gap analysis to delineate the current obstacles and technical deficiencies hindering widespread industrial adoption. The extracted challenges are categorised into:

- ✓ Kinematic and Spatial Barriers: Limited dexterity and high collision risks inside highly congested spaces (such as 1200 mm double-bottom blocks).
- ✓ Programming Overheads: The high computational time required for offline programming and seam tracking in non-standard configurations.
- ✓ Economic Barriers: High initial capital expenditure for custom robotic setups compared to flexible manual labour.
- ✓ Establish the state-of-the-art in structural optimisation and its lack of manufacturing integration.

3.2 Comparative Production and Economic Evaluation

This phase conducts a comparative analysis between conventional manual welding and robotic welding to establish the baseline for automated production (Moghaddam et al., 2018), specifically focused on ship double-bottom structures (Wahidi et al., 2023). The methodology for this evaluation includes:

- a. Performance Benchmarking: Quantifying welding speeds and cycle times. The study identifies that robotic systems can operate faster than manual methods in the specified naval context.
- b. Resource Consumption Analysis: Evaluating the efficiency of man-hours and energy. A comparative ratio was established for electricity and labour requirements between robotic and conventional approaches.
- c. Economic Value Analysis: Assessing the cost-effectiveness of robotic implementation to justify the capital investment for shipyard automation.

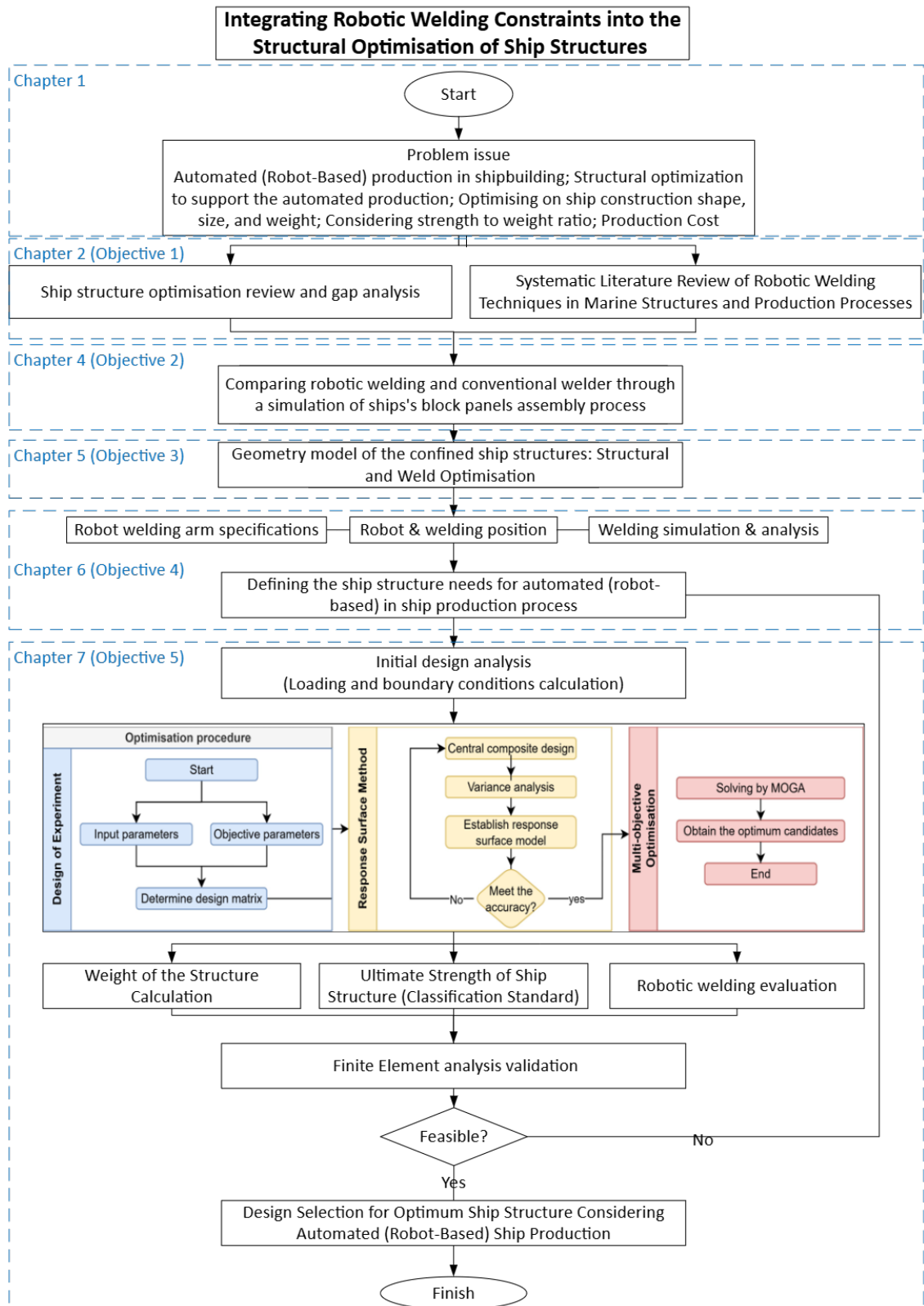


Figure 3-1 Research framework and methodology.

3.3 Structural Optimisation and Manufacturing Integration

The optimisation framework implemented in this phase focuses on resolving the inherent conflict between structural mass reduction and manufacturing efficiency within confined shipyard environments (Wahidi et al., 2025). The methodology is executed through the following structured sequence:

a. Algorithm Integration: MOGA and Response Surface Methodology

The mathematical optimisation model is established by integrating a Multi-Objective Genetic Algorithm (MOGA) with Response Surface Methodology (RSM) (Myers et al., 2016). RSM is utilised to construct highly accurate meta-models (surrogate models) of the ship structure from pre-computed finite element data. These meta-models serve as computationally efficient objective functions that allow MOGA to rapidly evaluate and navigate the complex design space without the need for continuous, time-consuming structural re-meshing.

b. Structural Variable Control: Constant Stiffener Count

To ensure high constructability and prevent unrealistic structural variations during the evolutionary process, the optimisation controls geometric variables by maintaining a constant stiffener count. Instead of altering the quantity of the structural members, which would drastically change the assembly workflow, the algorithm strictly modifies continuous scantling variables, such as plate thicknesses and stiffener cross-sectional dimensions. This constraint preserves the standard assembly sequence of the double-bottom block.

c. Multi-Objective Optimisation Formulation

The optimisation problem is formulated as a multi-objective challenge driven by two competing goals which are minimising Structural Mass to ensure fuel efficiency and material cost-reduction and minimising total weld length to directly reduce the cycle time and energy consumption of the welding process inside confined space.

d. Target Evaluation: Welding Reduction in Confined Spaces

The optimised structural output focuses on systematically reducing welding requirements inside the confined 1200 mm compartments. By prioritising geometric configurations that provide optimal spatial clearance and shorter joint lines, the framework directly addresses the physical limitations of the assembly join process, minimising welding path and minimising risk of the welding process inside the hazardous environment.

e. Safety and Cost-Reduction

The final phase validates that the Pareto-optimal designs simultaneously satisfy structural safety and manufacturing cost-reduction criteria. Structural integrity is rigorously verified against classification society rules (Lloyd's Register and IACS CSR) to guarantee that maximum equivalent stresses remain within the allowable limit (≤ 175 MPa) and satisfy 50-mode eigenvalue buckling requirements. Concurrently, the economic validation quantitatively evaluates production cost efficiency by coupling the structural optimisation outputs with a dedicated manufacturing cost function. The economic impact is determined through a dual-component formulation: (i) direct material cost savings, derived from the net reduction in structural steel mass multiplied by prevailing

commercial procurement unit rates per metric ton; and (ii) fabrication operational cost savings, quantified by calculating the reduction in confined-space arc welding time and labour man-hours.

3.4 Virtual Prototyping and Kinematic Framework

This phase involves the development of a Virtual Prototyping Framework (VPF) to evaluate the physical interaction between the robot and the ship structure.

- a. Robot Modelling: An industrial manipulator (IRB 1200) is modelled using ABB RobotStudio software to analyse its 6-axis kinematic behaviour.
- b. Spatial Constraint Analysis: The simulation environment replicates a 1200 mm height confined space, integrating various mounting configurations (floor, elevated, and inverted).
- c. Collision and Reachability Mapping: Automated path planning algorithms are tested to detect collisions between the welding torch and stiffener scantlings, providing data on reachability for different design variations.

3.5 Multi-Objective Structural Optimisation Integrating Robotic Constraints

The final phase develops an integrated multi-objective structural optimisation framework that incorporates robotic manufacturing constraints directly into the early design phase of a ship's double bottom block. The comprehensive workflow is structured into four sequential, integrated phases to bridge the gap between structural weight efficiency and automated welding accessibility within confined maritime spaces (Lee et al., 2011).

- a. Initial Setup and Automated Production Requirements

The process begins with the geometric modelling of the baseline midship double bottom block. Concurrently, automated production requirements are established by analysing the physical dimensions, joint limits, and kinematic envelopes of an ABB IRB 1200 robotic manipulator, which features an optimised 0.9 m reach radius. This reach capability allows the robot to execute a full, continuous U-shaped welding sequence to secure longitudinal stiffeners without intermediate base movements, minimising non-productive relocation cycles and alignment errors within the restricted 1,200 mm block height. The spatial requirements of the robot are explicitly formulated as numerical hard constraints within the multi-objective optimisation algorithm to establish the feasible boundary for the stiffener web height (h) and guarantee a zero-collision state. Within the confined double-bottom height ($H_{DB} = 1200$ mm), the vertical working clearance for the manipulator is governed by the relation:

$$C_{\text{vert}} = H_{DB} - h - h_{\text{robot_base}} \geq C_{\text{min}} \quad (3.1)$$

where $h_{\text{robot_base}}$ represents the mounting fixture height on top of the stiffener, and C_{min} is the minimum required vertical clearance derived from the robot kinematic sweep envelope. Concurrently, to avoid lower torch collisions and allow the welding head to negotiate the stiffener flange without mechanical interference, a lower geometric threshold is imposed on the stiffener web height ($h \geq 70$ mm). These kinematic thresholds are enforced as non-negotiable boundaries during the MOGA exploration, thereby automatically discarding any candidate scantlings that lead to structural interference.

b. Pre-Optimisation Numerical Studies

To establish a reliable baseline for structural evaluation, a high-fidelity Finite Element Analysis (FEA) model is developed. A systematic mesh convergence study is conducted by refining the element size from 500 mm to 50 mm to balance numerical accuracy with computational efficiency. The model is subjected to a hybrid boundary condition approach to simulate global hull continuity: the aft section is constrained via a rigid remote displacement ($UX, UY, UZ, ROTX, ROTY, ROTZ = 0$) to mimic a transverse bulkhead, while the forward cross-section is subjected to global longitudinal bending moments. Environmental and operational loads are applied simultaneously to represent a worst-case scenario, comprising external hydrostatic pressure on the shell plating and internal cargo pressure inside the tank. Finally, a standard earth gravity of the global acceleration is applied to account for the self-weight of the steel structure.

c. Multi-Objective Optimisation Procedure

The optimisation problem is formulated using a Multi-Objective Genetic Algorithm (MOGA) to resolve the trade-off between weight minimisation and manufacturing accessibility. First, a Design of Experiments (DoE) (Montgomery, 2017) matrix is constructed to sample the input parameters. Second, the Response Surface Method (RSM) utilising a Central Composite Design (CCD) (Myers et al., 2016) is applied to establish a high-fidelity surrogate model, mathematically mapping the non-linear relationships between design variables (plate thicknesses, web heights) and structural responses. The mathematical formulation targets two concurrent objective functions: minimising the total structural mass and minimising

the web plate height. This optimisation is governed by structural and operational constraints including keeping the maximum equivalent stress below the allowable limit of 175 MPa, maintaining total deformation within classification regulation limits, and ensuring a minimum clearance based on robotic welding simulation results.

d. Validation and Decision Making

The final phase executes a rigorous validation of the non-dominated Pareto-optimal candidates generated by MOGA. Selected optimum configurations undergo a full FEA re-evaluation to verify compliance with Lloyd's Register (LR) and IACS Common Structural Rules (CSR), focusing on maximum equivalent stress limits and structural deformations. Furthermore, elastic stability is verified through a comprehensive 50-mode eigenvalue buckling analysis under combined hogging and hydrostatic loads to ensure a robust safety factor against local and global buckling. Concurrently, the physical feasibility of the optimised scantlings is validated via high-fidelity welding path simulations in ABB RobotStudio. The optimum structural configuration is finalised only when both structural seaworthiness and collision-free robotic manoeuvrability are successfully satisfied.

Chapter 4. Simulation of a Ship's Block Panel Assembly Process: Optimising Production Processes and Costs through Welding Robots.

4.1 Chapter Outline

Robotic technology can be used to maximise welding work in difficult positions, such as joints in double-bottom construction. From an economic point of view, although the required initial investment is high, robotic welding can be used sustainably over time. Therefore, it is important to compare robotic welding with conventional welding. This chapter compares robotic welding and conventional welding from technical and financial perspectives, using a complex structure such as a double bottom as an example. The technical aspect of the comparison is related to the time it takes for a welding robot to join a double-bottom structure, which is then compared to the time it takes for this using conventional welding. In addition, the economic aspect of the comparison is related to the costs of operation and labour for robotic welding and conventional welding. In this chapter, the use of robotic welding for a ship's double-bottom assembly was simulated and analysed in terms of both technical and economic performance. The goal was to identify opportunities for process optimisation and cost reduction.

4.2 Methodology

In this chapter, a comparison is made between robotic welding and conventional welding in the assembly of a ship's block panels. The simulation focuses on a ship's double-bottom structures, which are explained in the following section.

4.2.1 Ship's Double-Bottom Construction

The double-bottom structure of the ship, as depicted in Figure 4-1, is one of its most crucial components. It is designed to withstand the hydrostatic forces that act on the bottom of the hull, as well as the weight of the freight.

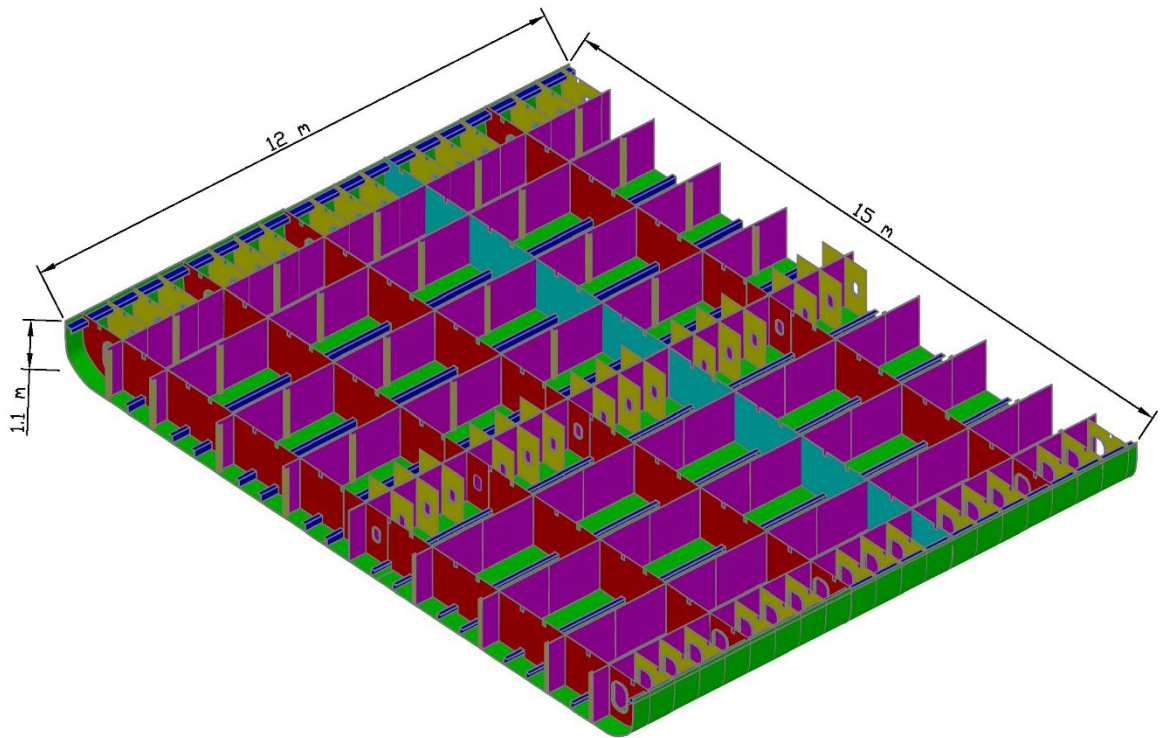


Figure 4-1 Ship double-bottom structure.

The ship's hull is essentially formed of bent plates that are joined by welding. If these plates are not stiffened, the bending moments caused by the loads may lead to more stress than the amount of stress that the material can withstand, which can then lead to failure. Stiffeners make the plates stiffer, which helps to prevent failure (or increases their section modulus).

The shipbuilding process has two phases: design and construction. The design phase involves converting the owner's requirements into a ship design that can be used

to build the ship. The ship's double bottom is built by assembling individual parts into panels, blocks, and then the entire structure, as shown in Figure 4-2 (Eyres & Bruce, 2012). The process of assembling a hull structure is similar to the process of assembling other floating structures, such as a floating dock (Wahidi et al., 2022). The sub-assembly stage involves joining the parts that were fabricated in the previous stage. A component block is created by combining the products of the cutting and shaping conducted by the fabrication workshop, including brackets, plate flooring, and face plates. At this stage, fitting, welding, and grinding are all part of the process.

Welding procedures utilising the unit panel method are commonly employed in the construction of large ships, as this approach offers improved work efficiency compared to traditional methods. In this method, panels with longitudinal stiffeners are first prepared and welded to the skin material through submerged arc welding (Oliveira & Gordo, 2018). The assembly process consists of several steps, as shown in Figure 4-2.

Initially, a bottom plate that has precisely the same form as that of the top plate is fabricated. Afterward, various transverse web floors and girders are joined onto the inner bottom plate. In the second step, the prepared unit panels, with longitudinal stiffeners, are placed on the open block in their correct locations (Lee et al., 2011). Finally, the unit panels are welded to the open block along the stiffeners, ensuring a secure fit.

After the unit panels are welded to the open block, the solid block is welded. The welding must be carried out from inside the solid block, along the edges where the

inner bottom panel and the bottom panel meet. The unit panel method makes the construction process more efficient, especially for large ships.

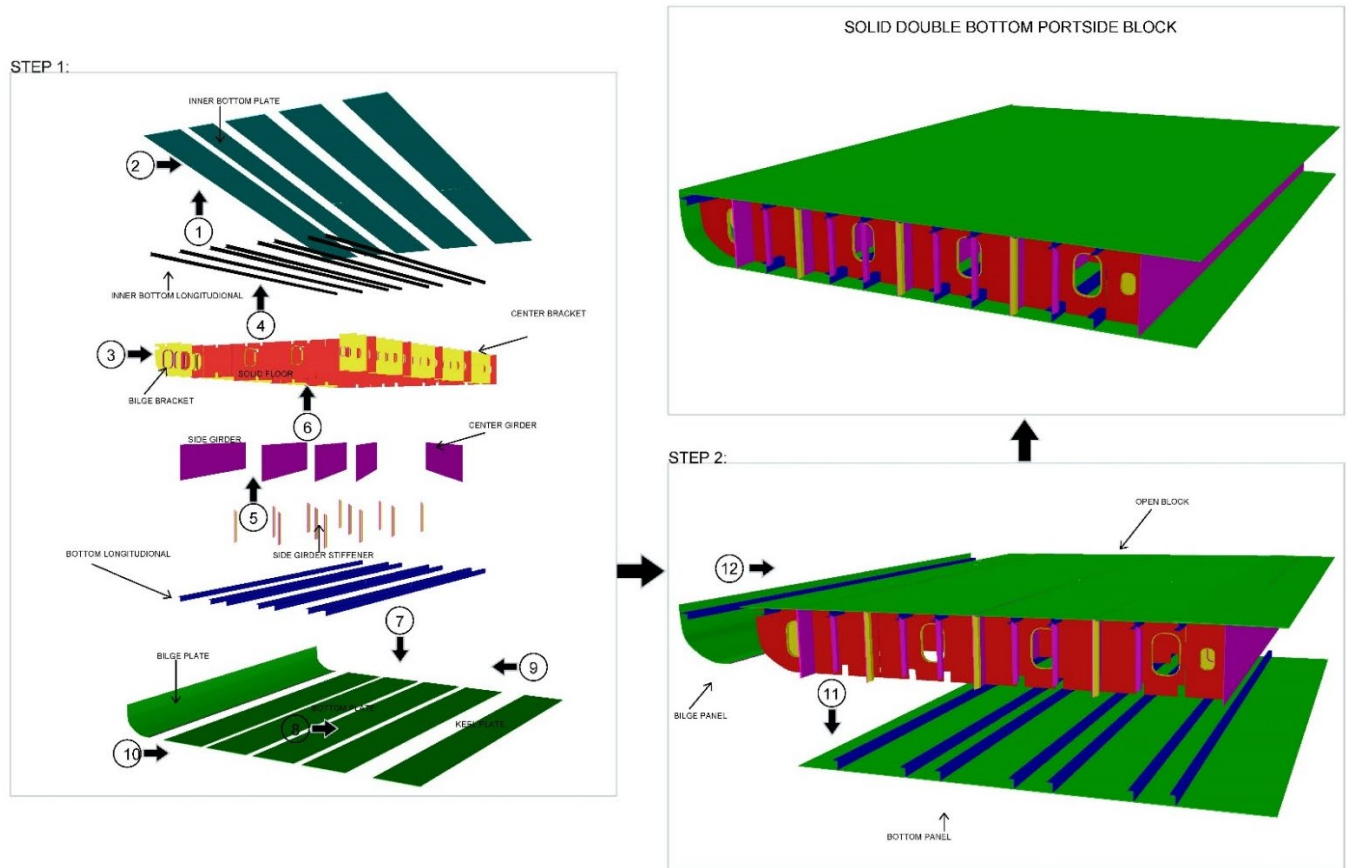


Figure 4-2 Ship double-bottom production stages.

4.2.2 Robotic Welding Specifications Used for Simulation

Robotic welding has become an increasingly popular technology in manufacturing and production processes due to its ability to increase productivity, quality, and efficiency while reducing costs (Okumoto, 1997). Robotic welding is particularly effective for repetitive welding of parts with similar structures and simple parts with high volume and joining piece parts that require a high degree of physical effort from welders. Furthermore, it is well-suited to welding common structures or

standard parts that are used in many different ships, making it a cost-effective solution for shipbuilding.

In the production of a double-bottom ship, a robotic welding machine must be able to move in various directions to reach all necessary welding points. Therefore, the robot arm specifications used must have six degrees of freedom, as shown in Figure 4-3. In this simulation, the specifications of the Kawasaki RS015X robot arm are utilised to analyse the welding reach for panel assembly. The robot's six degrees of freedom allow it to move in a variety of ways, including arm rotation, arm out-in, arm up-down, wrist swivel, wrist bend, and wrist twist, providing the necessary flexibility and precision to perform a wide range of welding tasks. The high level of precision and accuracy provided by the robot's six axes of movement make it well-suited for tasks that require a high degree of accuracy and repeatability (Oyama et al., 2007).

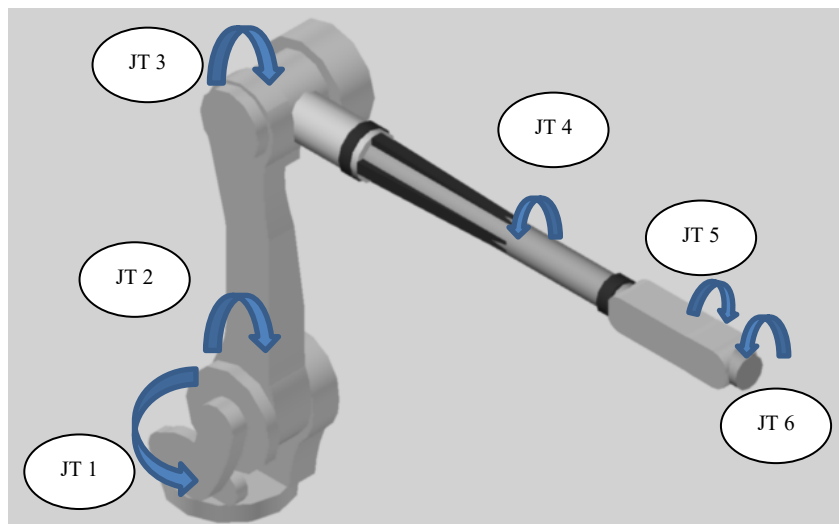


Figure 4-3 Six axes' movements of the robotic welding.

The robot has six axes of movement, each of which has a wide range of motion and high speeds, as shown in Figure 4-4. On the first axis, known as arm rotation (JT

1), the robot can rotate up to ± 180 degrees and move at a speed of 180 degrees per second. On the second axis, arm out-in (JT 2), the robot has a range of $+140$ degrees to -105 degrees and a speed of 180 degrees per second. The third axis, arm up-down (JT 3), has a range of $+135$ degrees to -155 degrees and a speed of 200 degrees per second. On the fourth axis, wrist swivel (JT 4), the robot can swivel up to ± 360 degrees and move at a speed of 410 degrees per second. On the fifth axis, wrist bend (JT 5), the robot has a range of ± 145 degrees and a speed of 360 degrees per second. On the sixth and final axis, wrist twist (JT 6), the robot can twist up to ± 360 degrees and move at a speed of 610 degrees per second.

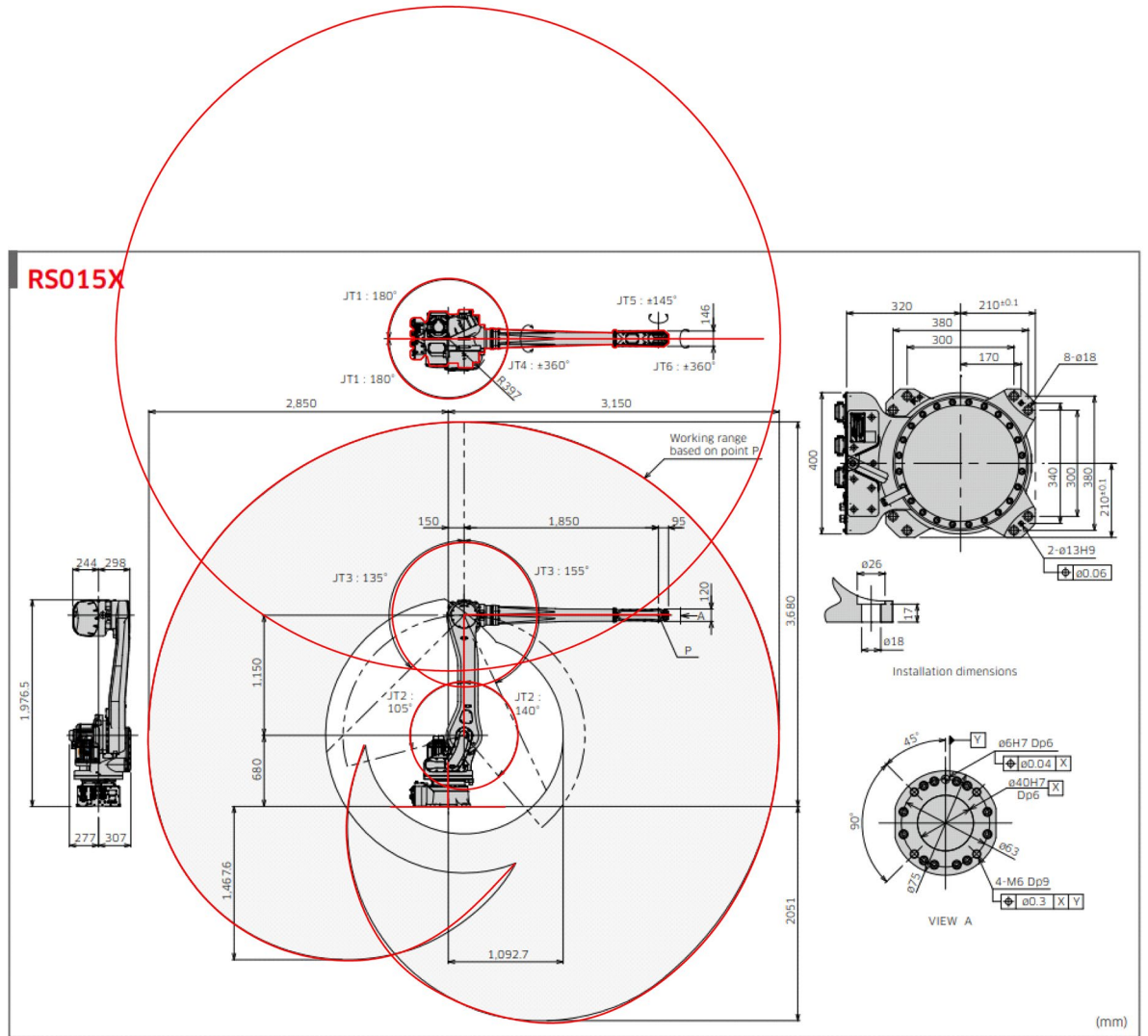


Figure 4-4 The range of the robotic welding arm.

4.2.3 Robotic Welding Procedure

The initial step in the robotic welding procedure involves joining the outer plates, which have been fabricated based on the cutting plan design, with longitudinal stiffeners, using submerged arc welding (SAW). This process forms the inner bottom panel. To achieve an efficient welding speed, the robotic welding travel speed of 1.5 m/min or 25 mm/s is combined with the arm speed, following the high-speed one-side

submerged arc welding process (Oyama et al., 2007). To calculate the welding time, the length required to weld 8 longitudinal stiffeners, each measuring 12 m, is analysed.

To optimise the movement and speed of the robot arm, the area for welding the inner bottom panel is divided based on the specified range and speed of the robot, as outlined in the specifications. The panel consists of plates measuring 12 m $\times$ 1.5 m with a thickness of 12 mm and is supported by 12 m long longitudinal stiffeners. This division enables determination of the robot's optimal movement and arm speed during the welding process.

In the subsequent stage, a simulation is performed to analyse the robot welding process for the double-bottom stiffeners. This simulation focuses on assessing the reachability of the robot arm within the specific conditions of the baseline robot, positioned at the height of the double-bottom structure. Given the complexity of the structure's design, a comprehensive 3D simulation is utilised to accurately identify the areas accessible by the robot arm. The robotic welding travel speed of 1500 mm/min or 25 mm/s, as specified by the A7 MAG Welder's 350/450 specifications, incorporates the arm speed.

Subsequently, the total time required to join the ship's double bottom is utilised for an economic analysis, comparing the costs of conventional welding and robotic welding. The economic aspect primarily focuses on comparing operational costs and direct labour expenses between the two welding methods.

4.3 Results and Discussion

In this section, the utilisation of robotic welding for a ship's double-bottom assembly is simulated and analysed, considering both technical and economic performance. The results derived from technical and economic analysis are presented and discussed.

4.3.1 Technical Analysis

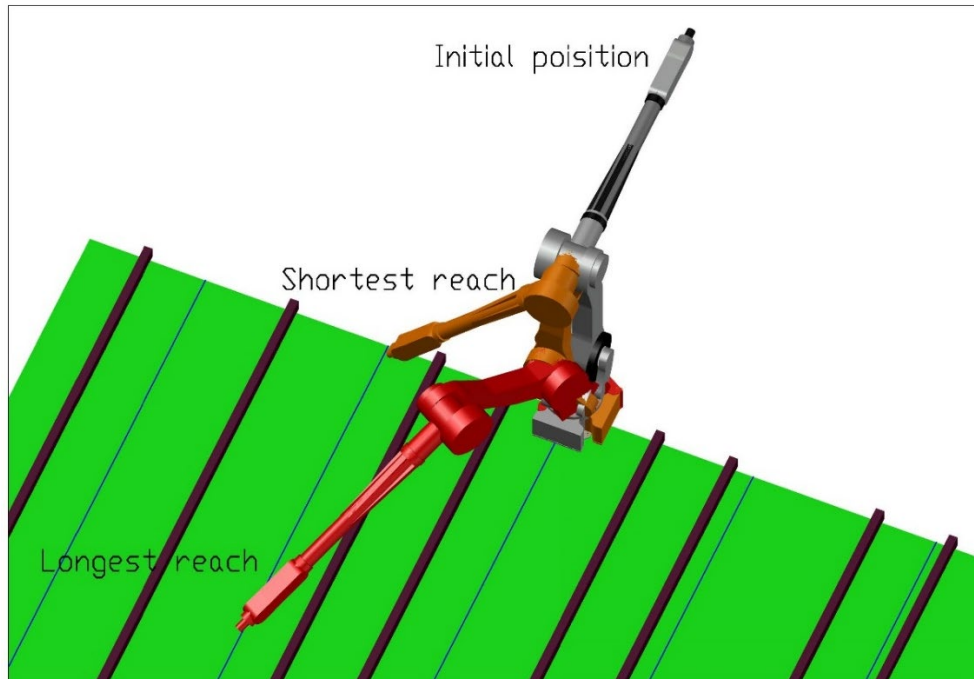
Welding quality is crucial for hull strength and ship safety. When initial cracks occur in the main structure, the critical applied torque is sharply reduced (Nguyen & Oterkus, 2020). According to Hong et al. (2021), fillet welded connections perform worse under fatigue as the length of the unwelded zone increases. Consequently, to avoid stress concentration and fatigue cracks, the welding junction must be executed perfectly, with a precise bead shape. The effectiveness of automatic welding techniques should be carefully considered by considering factors such as welding quality, the working environment, and cost efficiency, which includes both initial investments and operational costs. Due to the scope and complexity of the bottom structure, using the positioning system is essential for the successful implementation of robot welding. In this study, the positioning system is divided into two categories: outer panel joining and stiffener joining.

4.3.1.1 Outer Panel Joining

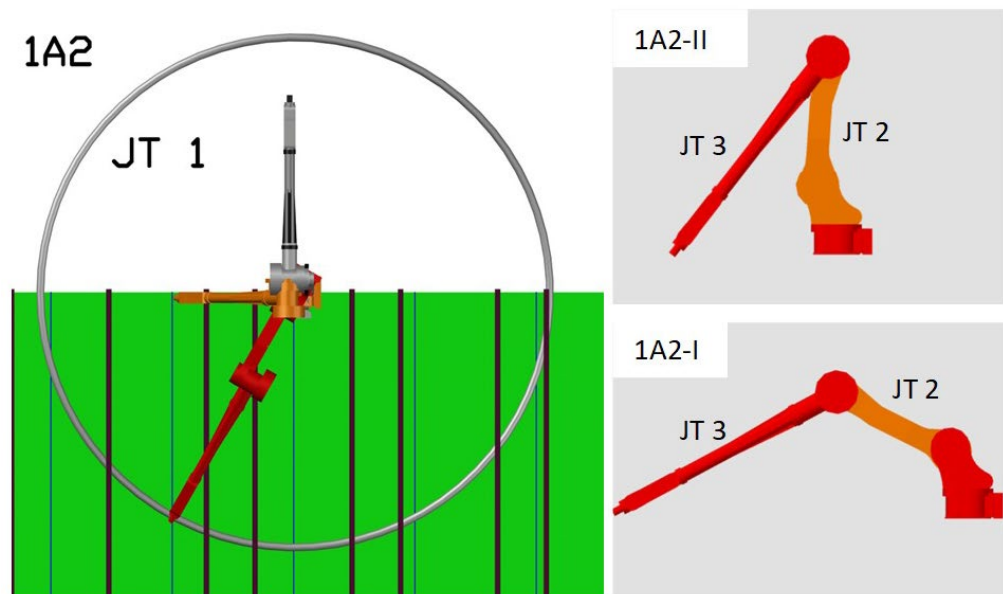
The outer plates are joined with longitudinal stiffeners using submerged arc welding (SAW) to form the inner bottom panel. The plates are fabricated according to the cutting plan design. The welding time calculation is conducted by first analysing the welding length required to weld eight longitudinal stiffeners, each measuring 12

m. A 5% welding margin is added to the total welding length, resulting in a length of 403,200 mm. The total welding time is calculated by multiplying the welding length by the welding travel speed (1.5 m/min) based on the high-speed one-side submerged arc welding process (Oyama et al., 2007) and applying an 80% safety factor, resulting in 15,372.7 seconds. Finally, the plates that have been equipped with longitudinal stiffeners are joined to form the inner bottom panel.

The area for welding the inner bottom panels is divided based on the range and speed of movement of the robot. This is done to optimise the welding process. The division is carried out to determine the optimal movement of the robot and the speed of the robot arm during the welding process. Figure 4-5 shows a three-dimensional visualisation of the base plate welding process using robotic welding on the welding line. In Figure 4-5a, the silver colour represents the initial position of the robotic welding, where the robot performs the farthest welding range in red and the closest range in orange.



(a)



(b)

(c)

Figure 4-5 (a) Three-dimensional view of the arm range simulation ; (b) top view of the arm range; (c) side view of the arm range.

Figure 4-5b shows the top view of the robot welding process on the inner bottom panel for the portside section with position 1A based on the coverage area of JT 1. The panel consists of plates measuring $12\text{ m} \times 1.5\text{ m}$ with a thickness of 12 mm and is supported by longitudinal stiffeners, each measuring 12 m long. In that position, the robotic arm can weld 1A2 with a welding length of 2774.03 mm, as indicated by the blue line.

Figure 4-5c shows the side view of the movement of the welding robot arm with the coverage area of JT 2 and JT 3. The angle of arm movement is determined by the limitations of arm reach and robot arm length. This is necessary to reach the welding area. Position 1A2-I is the farthest point that the robot arm can reach in the welding groove, while 1A2-II is the closest point that the robot arm can reach in the welding groove. The speed of arm movement is determined based on the angle of arm motion. This allows the robot arm to reach positions 1A2-I and 1A2-II. According to the analysis of the movement and range of the robot, it was found that the robot moved 16 times for the port side and starboard side, as shown in Figure 4-6.

According to the maximum reach of the robot arm, the robot welding is transferred from the first to the eighth position, as shown in Figure 4-6. The transfer is supported by a railway to ensure optimal productivity and quality. The railway serves as a track for the robot arm to move along, providing stability and reducing the risk of damage to the workpiece. This allows the robot to move seamlessly from one position to another, without the need for additional setup or repositioning. Additionally, using

a railway system can also help to optimise the robot's trajectory, reducing the likelihood of collisions or other issues during the transfer process.

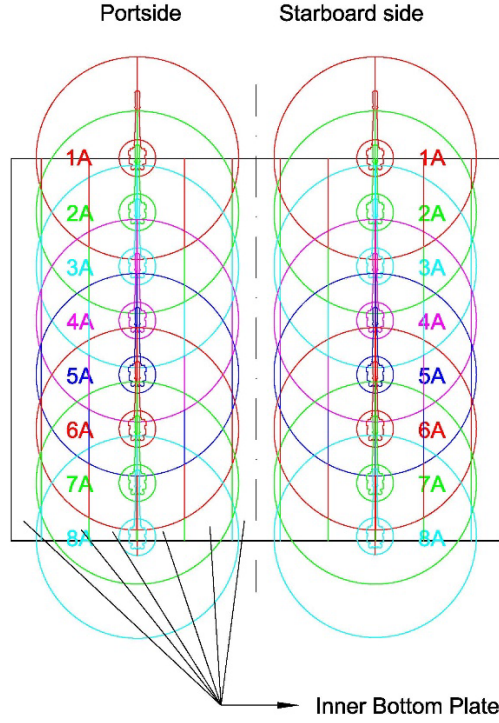


Figure 4-6 Robot transfer simulation.

The motion trajectory duration corresponding to the arm range simulation (Figure 4-5) is calculated from the individual angular displacements and the rated speed specifications of the six articulated joints, as summarised in Table 4-1. The travel duration for each respective axis (t_i) is determined by:

$$t_i = \frac{\Delta\theta_i}{\omega_i} \quad \text{for } i \in \{1, 2, \dots, 6\} \quad (4.1)$$

where $\Delta\theta_i$ represents the cumulative angular displacement (in degrees) traversed by joint i between the initial home posture and extreme workspace limits, and ω_i denotes the manufacturer-rated angular velocity (in $^\circ/\text{s}$).

In this kinematic sequence, the primary positioning axes (JT1, JT2, and JT3) govern the gross spatial translation of the manipulator across the stiffened block compartment and operate sequentially to avoid collision with surrounding web stiffeners. Conversely, the wrist articulation axes (JT4, JT5, and JT6), perform localised torch re-orientation concurrently within the time window established by the primary joints. Consequently, the total non-welding motion time (t_{motion}) is governed by the cumulative duration of the three major positioning joints:

$$t_{\text{motion}} = \sum_{i=1}^3 t_i = t_{\text{JT1}} + t_{\text{JT2}} + t_{\text{JT3}} \quad (4.2)$$

This kinematic formulation accounts for both the physical reach envelope shown in Figure 4-5 and the discrete motion times utilised in the overall panel cycle-time calculation.

Based on the analysis of the movement of the robot arm, the total motion time is obtained, as shown in Table 4-1. The grey column shows the specification of the robot arm used in this study. The total motion time for each robot movement is obtained by adding up the total angles achieved by joining, as shown in Figure 4-6. From these scenarios, the length of the weld performed in each scenario of the robot arm movement can also be calculated, as shown in Table 4-2.

Table 4-1 Motion time of the robotic arm required to join the inner bottom panel.

Part	Code	JT 1	JT 2	JT 3	JT 1	JT 2	JT 3	JT 4	JT 5	JT 6	JT 1	JT 2	JT 3	Total Motion Time
		Arm angle (degree)			Robot speed (degree/s)						Movement time (s)			s
Inner Bottom Panel	1A	682	416	272	180	180	200	410	360	610	3.8	2.3	1.4	7.46
	2A	786	487	250	180	180	200	410	360	610	4.4	2.7	1.3	8.32
	3A	786	648	245	180	180	200	410	360	610	4.4	3.6	1.2	9.19
	4A	786	648	245	180	180	200	410	360	610	4.4	3.6	1.2	9.19

Part	Code	JT 1	JT 2	JT 3	JT 1	JT 2	JT 3	JT 4	JT 5	JT 6	JT 1	JT 2	JT 3	Total Motion Time
		Arm angle (degree)			Robot speed (degree/s)						Movement time (s)			s
	5A	786	648	245	180	180	200	410	360	610	4.4	3.6	1.2	9.19
	6A	757	648	329	180	180	200	410	360	610	4.2	3.6	1.6	9.45
	7A	916	691	254	180	180	200	410	360	610	5.1	3.8	1.3	10.20
	8A	368	408	116	180	180	200	410	360	610	2	2.3	0.6	4.89

In order to comprehensively analyse the factors impacting welding quality, it is crucial to consider the welding position factors, as delineated in Table 4-2. These position factors are integral to the welding process, as they encompass varying levels of difficulty and directly influence the overall quality and strength of the welds. Some common welding positions are down hand (or flat position) and vertical positions, each of which presents unique challenges to the welder. The down hand position typically allows for easier manipulation of the welding torch or electrode, resulting in a more consistent weld bead and fewer defects. In contrast, the vertical position demands a higher level of skill and precision from the welder, as the molten weld pool is subject to gravitational forces that can affect the weld's integrity. Consequently, recognising and accounting for these position factors is essential to understand the factors that contribute to welding quality and develop strategies to optimise welding processes in various applications.

To accurately model the production cycle, the operational duration of the robotic welding cell is decomposed into two distinct kinematic phases, as summarised in Table 4-2:

1. **Welding Time (Arc-on Time):** The duration during which the electric arc is actively engaged and filler wire is deposited along the joint seams at the specified welding travel speed (e.g., $v_w = 25 \text{ mm/s}$).
2. **Motion Time (Non-welding / Air-cut Time):** The non-productive kinematic travel duration during which the arc is extinguished. This comprises rapid repositioning between consecutive stiffener bays, approach and retract tool motions, torch re-orientation manoeuvres across complex joint corners, and tactile seam-sensing intervals.

Consequently, the Total Time represents the complete automated cycle time:

$$\text{Total Cycle Time} = t_{\text{welding}} + t_{\text{motion}} \quad (4.3)$$

Table 4-2 Total time taken to join the inner bottom panel using robot welding.

Part	Code	Total Motion Time (s)	Weld Length (mm)	Both Side	Symmetric	Weld Layer	Total Weld Length (mm)	Total (+Margin 5%) (mm)	Welding Time (s)	Welding Position	Total Time (s)
Inner Bottom Panel	1A	7.46	7571.56	2	2	1	30,286.24	31,800.55	1211.4	Down hand	1218.9
	2A	8.32	7029.16	2	2	1	28,116.64	29,522.47	1124.7	Down hand	1133.0
	3A	9.19	8562.32	2	2	1	34,249.28	35,961.74	1370.0	Down hand	1379.2
	4A	9.19	8562.32	2	2	1	34,249.28	35,961.74	1370.0	Down hand	1379.2
	5A	9.19	8562.32	2	2	1	34,249.28	35,961.74	1370.0	Down hand	1379.2
	6A	9.45	10,302.3	2	2	1	41,209.28	43,269.74	1648.4	Down hand	1657.8
	7A	10.20	7204.53	2	2	1	28,818.12	30,259.03	1152.7	Down hand	1162.9
	8A	4.89	1671.84	2	2	1	6687.36	7021.73	267.5	Down hand	272.4

Furthermore, the speed of the arm is added to the robotic welding travel speed of 1.5 m/min, or 25 mm/s, based on the high speed one-side submerged arc welding process (Oyama et al., 2007). The total welding time is obtained by adding a margin and safety factor. This is shown in Table 4-2.

4.3.1.2 Stiffener Joining

In the subsequent stage of the research, a simulation is conducted to analyse the robot welding process for the double-bottom structure. This simulation focuses on determining the reachability of the robot arm based on its range and the specific conditions of the baseline robot positioned at the height of the double-bottom structure. The complex design of structure required a comprehensive 3D simulation to precisely identify the areas that the robot arm could reach.

The 3D simulation was used to carefully examine the welding area and determine the specific piece parts that fall within the range of the robot arm. The simulation took into account the spatial constraints and dimensions of the structure, enabling an accurate assessment of the areas where the robot arm can effectively perform the welding operation.

The welding zones were divided into outer and inner zones based on the reach of the robot arm. This was done for both the port and starboard sides of the double-bottom structure. This division allowed for a systematic and efficient approach to the welding process. Figure 4-7 visually represents the simulation results, showcasing the optimal areas for welding. The outer 1 (O1) area is depicted in green, indicating the region that is successfully reached and welded by the robot arm. Similarly, the inner 1 (I1) area is represented in blue, signifying the portion accessible for welding. The magenta-coloured outer 2 (O2) area represents another region within the reach of the robot arm, while the red-coloured inner 2 (I2) area designates an additional accessible section.

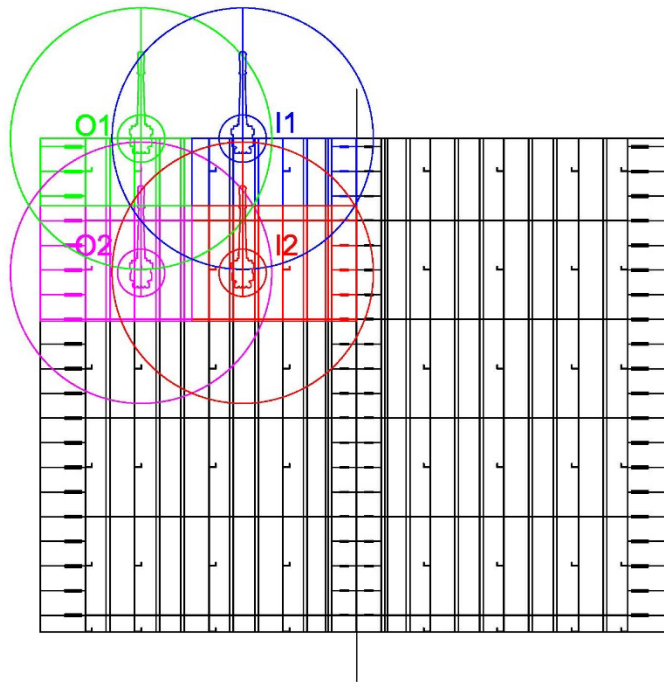


Figure 4-7 Simulation of robot arm reach when welding the double-bottom structure.

In addition, the arm speed is incorporated into the robotic welding travel speed of 1500 mm/min or 25 mm/s, as specified by the A7 MAG Welder's 350/450 specifications using carbon steel filler material. The total welding time for each piece is determined by considering the margin and applying a safety factor. Table 4-3 provides an example of the outer and inner calculation. Subsequently, the same calculation procedure can be applied to all joining piece parts up to the fifth outer and inner zones for both the starboard and port sides.

Table 4-3 Outer and inner calculations for assembling the stiffeners by robotic welding.

Piece Part	Code	Total Weld Length (mm)	Total (+Margin 5%) (mm)	Welding Time (s)	Welding Position	Welding Position Factor	Total Time (s)
Bilge Floor—Plate	O1	22,728.00	23,864.40	909.1	Down hand	1	921.9
Bilge Floor—Side Girder		29,700.00	31,185.00	1188.0	Vertical	1.5	1200.7

Piece Part	Code	Total Weld Length (mm)	Total (+Margin 5%) (mm)	Welding Time (s)	Welding Position	Welding Position Factor	Total Time (s)
Side Girder—Plate		13,070.48	13,724.00	522.8	Down hand	1	535.5
Side Girder Stiff.—Side Girder		8800.00	9240.00	352.0	Vertical	1.5	364.7
Centre Bracket—Plate		7200.00	7560.00	288.0	Down hand	1	300.7
Centre Bracket—Centre Girder		13,200.00	13,860.00	528.0	Vertical	1.5	540.7
Side Girder—Plate	I1	13,070.48	13,724.00	522.8	Down hand	1	535.5
Side Girder Stiff.—Side Girder		8800.00	9240.00	352.0	Vertical	1.5	364.7
Centre Girder—Plate		3267.62	3431.00	130.7	Down hand	1	143.4
Long. Stiff—Watertight Floor		3420.00	3591.00	136.8	Down hand	1	149.5
Long. Stiff—Solid Floor		3420.00	3591.00	136.8	Down hand	1	149.5
Bilge Floor—Plate		22,728.00	23,864.40	909.1	Down hand	1	921.9
Bilge Floor—Side Girder		19,800.00	20,790.00	792.0	Vertical	1.5	804.7
Side Girder—Plate	O2	22,468.40	23,591.82	898.7	Down hand	1	911.5
Side Girder—Side Girder Stiff.		8800.00	9240.00	352.0	Vertical	1	364.7
Side Girder—Floor		8800.00	9240.00	352.0	Vertical	1.5	364.7
Side Girder—Watertight Floor		8800.00	9240.00	352.0	Vertical	1.5	364.7
Solid Floor—Plate		18,810.20	19,750.71	752.4	Down hand	1	765.1
Watertight Floor—Plate		18,810.20	19,750.71	752.4	Down hand	1	765.1
Long. Stiff—Watertight Floor		4560.00	4788.00	182.4	Down hand	1	195.1
Long. Stiff—Solid Floor		4560.00	4788.00	182.4	Down hand	1	195.1
Centre Bracket—Plate		7200.00	7560.00	288.0	Down hand	1	300.7
Centre Bracket—Centre Girder		13,200.00	13,860.00	528.0	Vertical	1.5	540.7
Side Girder—Plate		22,468.40	23,591.82	898.7	Down hand	1	911.5
Side Girder—Side Girder Stiff.	I2	8800.00	9240.00	352.0	Vertical	1.5	364.7
Side Girder—Floor		8800.00	9240.00	352.0	Vertical	1.5	364.7
Side Girder—Watertight Floor		8800.00	9240.00	352.0	Vertical	1.5	364.7
Centre Girder—Plate		5617.10	5897.96	224.7	Down hand	1	237.4
Solid Floor—Plate		16,057.60	16,860.48	642.3	Down hand	1	655.0
Watertight Floor		16,057.60	16,860.48	642.3	Down hand	1	655.0

The welding area is divided into different zones based on the reach of the robot's arm, specifically JT1, JT2, and JT3. The baseline position for the robot is set at the height of the double bottom, as shown in Figure 4-8. This helps to optimise the reach and movement of the robot. The length and angle of the welding area are then measured in the outer and inner zones (O1/I1–O5/I5), based on the reach of the robot arm. This analysis identifies 20 optimal positions for welding in the construction of the double bottom.

Furthermore, to ensure the robot arm can effectively reach the welding area of various construction components, such as side girders and brackets, the angle of the arm is measured using motions JT2 and JT3. This information enables the determination of the robot arm's movement speed. Figure 4-9 provides a visualisation of the arm reach simulation specifically for stiffener welding.

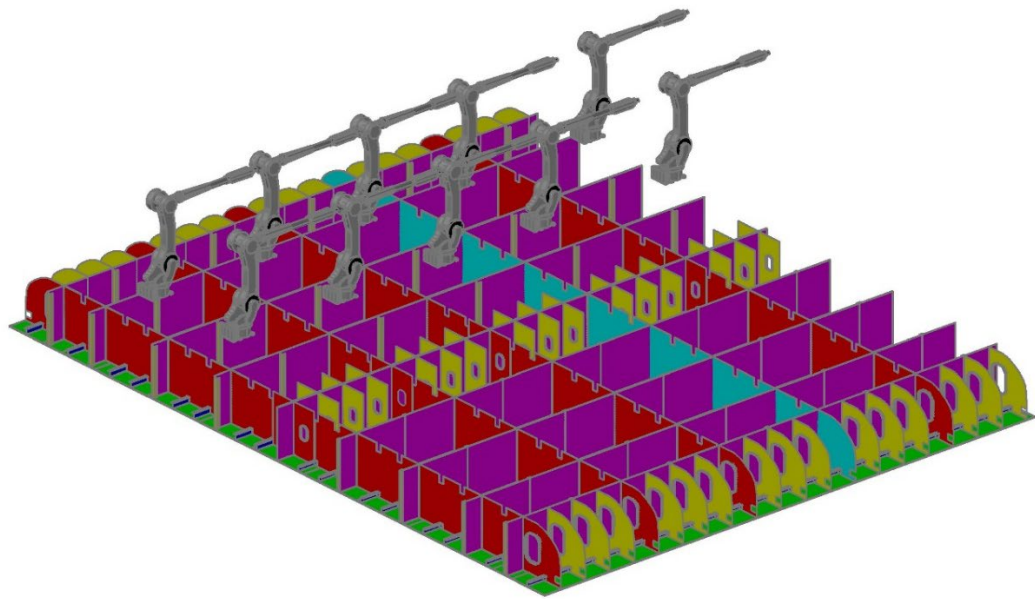


Figure 4-8 Positioning of the robot welding in the double-bottom assembly process.

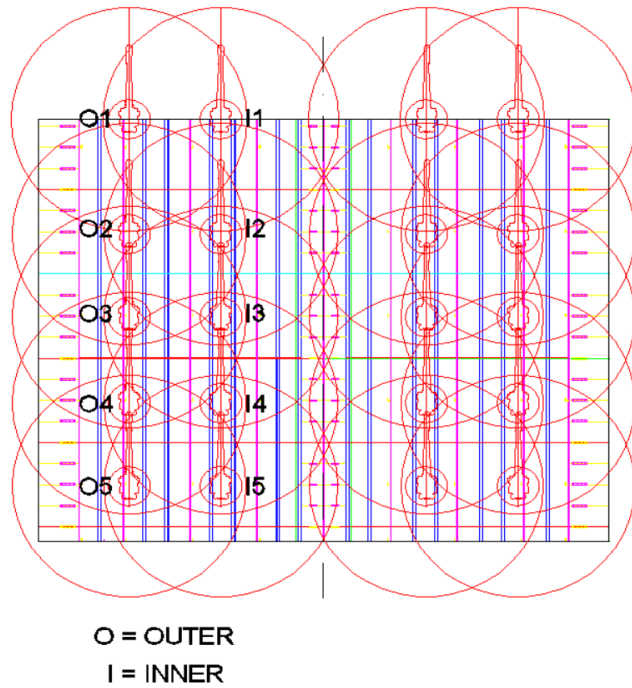


Figure 4-9 Simulation of robot welding movement on the double bottom.

The simulation helps to optimise the welding process for the double-bottom structure by systematically dividing the welding area, measuring the optimal positions, and assessing the arm movement. The simulation outcomes provide valuable insights into the feasibility and effectiveness of the robot welding process for the double-bottom structure. The simulation helps to streamline the welding operations by accurately identifying the optimal areas for welding. This ensures that the robot arm can efficiently carry out the required tasks within the specified zones.

The welding time for a double-bottom block from a general cargo ship measuring 12 m in length, 15 m in breadth, and 1.1 m in depth is determined to be 17.42 h, based on the analysis of the results and considering the welding robot displacement scenario, as shown in Table 4-4. In comparison to conventional welders, the assembly process of the double-bottom panel is carried out by certified welders

specialised in the field of shipbuilding, with minimum qualifications of 1G (Flat), 2G (Horizontal), 3G (Vertical), and 4G (Overhead) positions. When employing conventional Flux Cored Arc Welding (FCAW) using carbon steel filler material with a welding speed of 6.7 mm/s (Sá de Sousa et al., 2021), the welding time is estimated to be 67.12 h. This calculation is obtained by multiplying the welding length achieved using the conventional welding speed for FCAW.

Table 4-4 Total time of the double-bottom block welding process.

Part	Weld Length (mm)	Weld Length (+Margin 5%) (mm)	Welding Time (s)	Total Welding Time (s)
Long. Stiff—Plate	384,000.00	403,200.00	15,360.0	15,372.7
Inner bottom panel	237,865.48	249,758.75	9514.6	9582.5
Zone O1	74,298.48	78,013.40	2971.9	3022.9
Zone I1	45,538.10	47,815.01	1821.5	1885.2
Zone O2	135,856.80	142,649.64	5434.3	5561.6
Zone I2	116,120.70	121,926.74	4644.8	4784.9
Zone O3	94,086.08	98,790.38	3763.4	3852.6
Zone I3	82,606.90	86,737.25	3304.3	3406.1
Zone O4	90,261.12	94,774.18	3610.4	3699.6
Zone I4	80,065.20	84,068.46	3202.6	3304.5
Zone O5	106,287.40	111,601.77	4251.5	4340.6
Zone I5	94,887.10	99,631.46	3795.5	3897.3
Total Weld Length			1,618,967.03	mm
			1618.97	m
			62,710.36	s
Total Welding Time (+ safety factor robot 80%)			1045.17	min
			17.42	h

To account for real-world shipyard operational uncertainties, an operational safety/efficiency factor of 80% was incorporated into the block assembly timeline presented in Table 4-4. While idealised offline simulation models assume continuous kinematic execution, practical automated fabrication environments are subject to non-cyclic delays. Specifically, this 20% operational margin accounts for:

1. Welding equipment maintenance routines, including periodic torch nozzle cleaning, anti-spatter spraying, wire clipping, and contact tip replacements;
2. Transient fit-up gap variations in structural steel plates resulting from prior thermal cutting and tack-welding distortions, necessitating sensory seam-tracking adjustments; and
3. Material handling latency and operator inspection intervals between sub-block transitions.

Applying an 80% operating factor aligns with standard industrial manufacturing allowance methodologies (Storch, 1995) and empirical Overall Equipment Effectiveness (OEE) benchmarks established for heavy maritime welding cells (Ferreira et al., 2017). The primary limitation of this factor is that it assumes standard operational conditions; severe downtime events, such as catastrophic component failure or major fit-up misalignments exceeding permissible classification tolerances, fall outside the deterministic scope of this baseline estimation.

The results of the study show that robotic welding is approximately 3.85 times faster than conventional welding. These results emphasise the significant time-saving advantage offered by robotic welding in comparison to the conventional approach.

4.3.2 Cost Comparison

In this section, an economic analysis is conducted to compare the costs of conventional welding and robotic welding. The discussion focuses on the cost of the components used in conventional welding for ship production. Subsequently, the costs of joining the double bottom through robotic welding are calculated. The estimations

from both approaches are analysed and compared to determine which method is more cost-effective.

The robotic welding equipment is 3.85 times faster than a conventional welder when joining the ship's double bottom, according to the technical analysis. Consequently, the operational cost calculation is conducted by considering four instances of conventional welding and comparing them with a single instance of robotic welding equipment.

The incorporation of the total time required to join the ship's double bottom as a determining factor in the calculation of electricity costs and man-hour costs has been recognised as a critical aspect of the research (González-González et al., 2023). This integration provides a more accurate and comprehensive assessment of the overall costs associated with the shipbuilding process, and it also allows for a deeper understanding of the relationship between time and cost optimisation.

In the analysis, various stages involved in the joining process have been carefully considered, taking into account the duration and complexity of each step. An accurate estimation of the resources required for the process can be achieved, including the electricity consumed during the welding and assembly stages, as well as the man-hours needed, by incorporating these factors into the calculations.

Moreover, the inclusion of time as a determining factor enabled the identification of potential bottlenecks and inefficiencies within the process. This led to the development of strategies for optimising both time and cost, which ultimately led to a more efficient and cost-effective shipbuilding process.

4.3.2.1 Comparison of the Use of Electricity Costs

The operational costs incurred when using welding machines vary significantly between robot welding machines and conventional welding machines. This difference is due to the fact that robot welding machines consume more power than conventional welding machines. Specifically, the power specifications of the welding machines play a significant role. The conventional welding machine used in this study consumes 3000 watts of power, while the robot welding machine consumes 4500 watts of power.

The estimated electricity costs for robot welding machines and conventional welding machines are presented in Table 4-5 and Table 4-6, respectively. Table 4-5 shows that the total electricity cost for constructing a double-bottom block using a single robot unit is GBP 37.81. Conversely, if four units of conventional welding machines are used, the electricity cost is GBP 100.82. The analysis reveals that the utilisation of a robotic welding machine can result in a substantial savings in electricity costs of 63% compared to conventional welding machines.

Table 4-5 Electricity cost per double bottom for robotic welding.

Items	Value	Unit
Welding robot operating hours per day	8	h
The current used (information based on a survey of welding wire products)	320–500	Amps
Welding robot device power	4500	Watt
Power consumption of electricity for welding robot	36	kWh
Number of welding robot operators	1	Person
Number of welding robots	1	Unit
Cost of electricity per kWh (based on UK tariff)	0.32	GBP
Operation costs (Electricity consumption × Electricity cost per kWh)	11.58	GBP
Overhead cost per day (20%)	2.32	GBP
Margin (30%)	3.47	GBP
Electricity cost per operating hours per day (8 h)	17.36	GBP
Electricity cost per hours	2.17	GBP
Welding time	17.42	h
Electricity cost for a double bottom	37.81	GBP

Table 4-6 Electricity cost per double bottom for manual welding.

Items	Value	Unit
Welder operating hours per day	6	h
The current used (information based on a survey of welding wire products)	300–350	Amps
Welding machine power	3000	Watt
Power consumption of electricity for welding machines per day	18	kWh
Number of welders	4	People
Number of welding machines	4	Unit
Cost of electricity per kWh (based on UK tariff 2022)	0.32	GBP
Operation costs (Electricity consumption * Electricity cost per kWh)	23.15	GBP
Overhead cost per day (20%)	4.63	GBP
Margin (30%)	6.95	GBP
Electricity cost per operating hours per day (6 h)	34.73	GBP
Electricity cost per hours	5.79	GBP
Welding time (with 4 welders)	17.42	h
Electricity cost for a double bottom	100.82	GBP

4.3.2.2 Comparison of Direct Labor Costs

Labor costs are costs associated with labour needs during the production process. Direct labour costs are the costs associated with the salaries or wages of the workers who are directly involved in the production of a product. In this research, the man-hour cost is based on the average welder's salary per hour in the United Kingdom as reported in (Indeed, 2023).

The labour cost rate for the robotic welding operator was assumed to be equivalent to that of a certified manual welder. In modern shipyard fabrication, a robotic cell operator is not merely a machine attendant but is required to possess the domain knowledge of a skilled welder, including weld joint inspection, parameter adaptation, and metallurgical defect assessment, alongside robotic interface handling. Consequently, adopting the standard welder wage rate establishes a consistent and equitable baseline for the comparative techno-economic evaluation.

The direct labour cost for robotic welding in joining the double bottom panels is GBP 696.78, which includes the salaries of one robot operator, one fitter, and one helper, as shown in Table 4-7. In contrast, conventional welding is more expensive, with a total cost of GBP 1916.15, including the salaries of four welders, two fitters, and two helpers, as shown in Table 4-8. The analysis shows that using a robotic welding machine can save GBP 1219.37, or approximately 64% of the total man-hour costs incurred by conventional welding methods, as shown in Table 4-7 and Table 4-8.

Table 4-7 Man-hour cost for robotic welding (GBP).

No	Worker	Qty	Fee/h	Fee/a Double-Bottom Block
1	Operator Robot	1	15.00	261.29
2	Fitter	1	15.00	261.29
3	Helper	1	10.00	174.20
SUM		3	40.00	696.78

Table 4-8 Man-hour cost for manual welding (GBP).

No	Worker	Qty	Fee/h	Fee/a Double-Bottom Block
1	Welder	4	15.00	1045.17
2	Fitter	2	15.00	522.59
3	Helper	2	10.00	348.39
SUM		8	40.00	1916.15

4.3.2.3 Cost Recapitulation

The results of calculations are presented in Table 4-9, which summarises the costs of electricity and man-hours for conventional welding and robotic welding. Table 4-9 shows that the total cost of electricity and man-hours for conventional welding is GBP 2016.97, while the total cost for robotic welding is GBP 734.59. By simultaneously reducing active arc times and minimising power demand across the fabrication cycle, the combined direct production expenditures, comprising electrical

energy consumption and direct labour man-hours, yield an overall cost ratio of 1:2.75 in favour of robotic welding. This comparison clearly demonstrates that the utilisation of robotic welding can significantly reduce operational costs.

Table 4-9 Comparison of the conventional welder and robot welding costs for a double-bottom block.

No	Items	Cost (GBP)		Note
		Conventional	Robot	
1	Electricity	100.82	37.81	Per Double-Bottom Block
2	Man-Hours (MH)	1916.15	696.78	Per Double-Bottom Block
	Total	2016.97	734.59	

The findings of this study demonstrate the substantial operational cost advantages of implementing robotic welding over conventional manual methods in ship block assembly. The reduction in operational expenditures is primarily driven by cumulative electricity consumption and a notable decrease in direct labour man-hours resulting from accelerated cycle times. These efficiency gains enable shipyards to streamline production workflows, mitigate ergonomics-driven labour shortages, and strengthen manufacturing competitiveness.

Nonetheless, it is essential to emphasise the inherent boundaries of this comparative cost model. The economic analysis presented in this chapter evaluates direct operational production costs (electricity and labour expenditures) within the boundaries of the double-bottom sub-assembly. The model intentionally excludes initial capital expenditures (CAPEX), such as robotic cell procurement, specialised end-effector tooling, positioning rails, and peripheral safety systems, as well as ongoing operational overheads, including system maintenance, routine calibration, and

workforce reskilling. Consequently, a comprehensive techno-economic feasibility study is recommended as an essential avenue for future research to establish enterprise-level investment viability.

Chapter 5. Structural Optimisation for Minimising Weight and Welding in Confined Shipbuilding Spaces: Enhancing Safety and Reducing Costs

5.1 Chapter Outline

The increasing demands for reduced weight and lower carbon emissions in modern shipbuilding necessitate advanced structural optimisation techniques, particularly within the challenging context of confined manufacturing spaces. Numerous studies on ship structural optimisation have focused on achieving lighter designs, primarily by increasing the number of stiffeners while reducing the thickness of base plates. However, such approaches often lead to higher production complexity, extended fabrication time, and increased costs, especially when introducing new stiffener types. Moreover, welding in confined spaces presents significant challenges related to worker safety and project scheduling. This chapter proposes a structural optimisation approach that not only minimises structural weight but also reduces the extent of welding required during assembly. A multi-objective genetic algorithm (MOGA) integrated with a response surface methodology and constraint rules classification is employed. The optimisation variables include plate thickness, stiffener thickness, and stiffener dimensions, while maintaining a constant number of stiffeners to avoid additional welding operations.

5.2 Methodology

This study employs a multi-objective structural optimisation framework to minimise both the weight of ship structures and the extent of welding required,

particularly in confined spaces (D. H. Kim & Paik, 2017). The methodology integrates a Multi-Objective Genetic Algorithm (MOGA) with Response Surface Methodology (RSM) and constraint rules classification to ensure feasible and practical design outcomes (R. Zhang et al., 2025).

5.2.1 Problem Definition

Ship structural design optimisation plays a crucial role in improving producibility, improving life-cycle performance, and ultimately reducing construction costs (L. Sun & Wang, 2011). A big part of this area involves designing basic structural parts like stiffened panels, which are used commonly in the construction of a ship (Aydin et al., 2020). This unit panel approach improves efficiency, particularly in the construction of large vessels. Once the unit panels are in place for a double-bottom assembly, a typical U-shaped boundary is welded internally at the joints between the inner and outer bottom plates, as shown in Figure 5-2. This involves welding along contacting boundaries between longitudinal stiffeners and transverse web floors or between the top and bottom shells as represented in red colour, in the space typically ranging from 2 to 3 meters between the outer and inner plates (Lee, 2013).

In this case, a common optimisation issue is set up with two main goals: to reduce the weight of the stiffened panel's structure and to shorten the welding length, especially for the web plates, which are very important in tight assembly spaces. Minimising structural weight is a long-established goal in shipbuilding, aiming to reduce material costs, increase deadweight capacity, and improve fuel efficiency (Ghadge et al., 2022). Simultaneously, the reduction of welding length directly correlates with decreased manufacturing effort and labour costs (X. Yang et al., 2018),

a factor of particular significance given that welding within the often challenging and confined structures of ships presents substantial practical and safety-related difficulties.

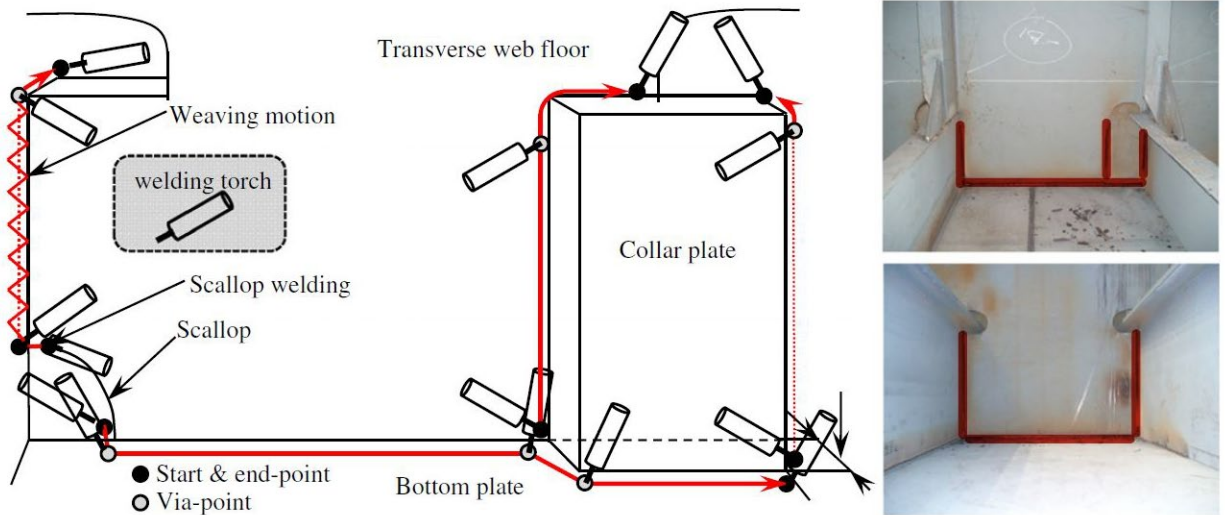


Figure 5-1 A typical U-shaped boundary to be welded in a double bottom structure (Lee et al., 2011)

This research addresses a critical trade-off between structural efficiency and production feasibility in the shipbuilding industry, specifically for the optimisation of a ship's double bottom structure. While existing structural optimisation studies have successfully minimised geometric mass, they often achieve this by increasing the number of stiffeners. Such an approach, though beneficial for reducing ship weight, significantly increases the welding quantity, a major concern in ship production. Furthermore, welding in the confined and enclosed space of a double bottom introduces substantial safety risks and extends production time. To mitigate these issues, this study adopts a novel optimisation approach. We maintain a constant number of stiffeners and instead focus on minimising the stiffener height (h). This is a

deliberate choice based on the fact that stiffener height is a direct and rational proxy for the welding length during the double bottom assembly process. As illustrated in Figure 5-1 (step 2) and Figure 5-2, the welding of web stiffeners to the web floor is a critical process, and reducing stiffener height directly reduces the overall length of these essential welding joints. Therefore, by minimising stiffener height, our structural optimisation not only reduces mass but also effectively minimises the dangerous and time-consuming welding processes within the double bottom, providing a more comprehensive and practical solution for naval architecture and production engineering.

5.2.2 Geometry model

The subject of this study is the stiffened plate, a fundamental component found in various parts of ship structures like decks, bottoms, and sides as illustrated in Figure 5-3. This type of plate consists of a flat steel plate with several stiffeners attached to it. For this research, the boundary conditions for the flat plate are set as fixed supports around its perimeter. The stiffened panel is subjected to self-weight and a uniformly distributed lateral load applied normal to its upper surface in the negative z-direction. In compliance with the Lloyd's Register (LR) Rules and Regulations for the Classification of Ships (Part 3, Chapter 3, Section 5: Design Heads and Permissible Cargo Loading), the design pressure (P) acting on the inner bottom plating is determined based on the maximum hydrostatic head of the internal liquid/cargo hold volume according to:

$$P = \rho \cdot g \cdot h_{\text{load}} \times 10^{-3} \quad [\text{kN/m}^2] \quad (5.1)$$

where ρ is the design cargo/ballast density ($\rho = 1.025 \text{ t/m}^3$ for standard marine density), g denotes the acceleration due to gravity (9.81 m/s^2), and h_{load} represents the vertical design head measured from the inner bottom plate to the top of the cargo hold or overflow air pipe (Lloyd's Register, 2024).

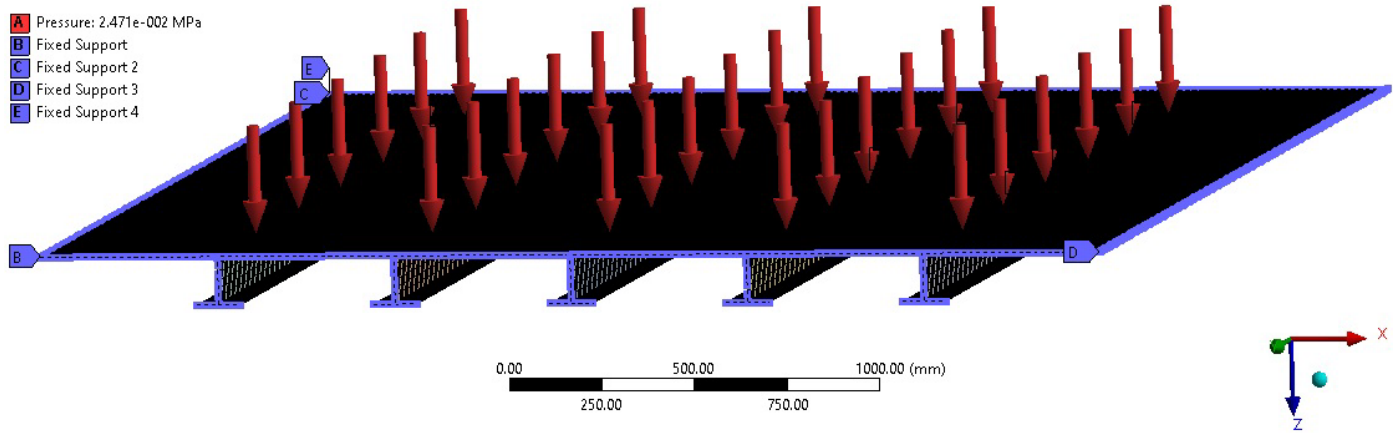


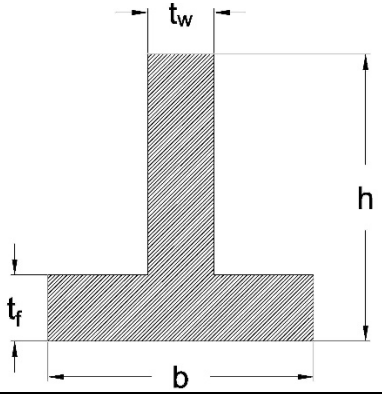
Figure 5-2 Stiffened plate model.

The physical and mechanical properties of the plate and stiffeners include a width (L_x) of 2935 mm, a length (L_y) of 3450 mm, and the material used is mild steel with a density of 7800 kg/m^3 . Additionally, there are 5 stiffeners, and the plate thickness is 10 mm. The initial stiffener design specifications include a height of 130 mm, a flange width of 120 mm, and a thickness of 7 mm, as presented in Table 5-1.

The methodology presented in this study, while demonstrated on a double bottom stiffened plate, possesses a broader applicability to other complex marine structures. The core framework, which integrates finite element analysis (FEA) for structural modelling with metaheuristic optimisation algorithms for design exploration, can be readily extended. For instance, the same approach could be used

to optimise the scantlings and arrangements of a ship's side shell, bulkheads, or even a complete hull structure. The key lies in the modularity of the framework; the FE model can be replaced with that of another structural component, and the optimisation algorithms can be reconfigured to handle different design variables and objective functions. This adaptability makes the proposed methodology a versatile tool for multidisciplinary design optimisation in naval architecture, offering a systematic and efficient way to explore complex design spaces beyond the specific case of double bottom structures.

Table 5-1 Initial design parameters for the stiffener.

No	Parameter	Initial design	
1	Base Plate thickness	10 mm	
2	Stiffener height / Web (h)	130 mm	
3	Web plate thickness (t_w)	7 mm	
4	Stiffener Flange / face (b)	120 mm	
5	Flange thickness (t_f)	7 mm	

5.2.3 Initial model analysis

The initial model was subjected to a static structural analysis using Ansys software. Fixed supports were applied along each side of the model as boundary conditions, simulating a representative section of the entire ship structure, as illustrated in Figure 5-4.

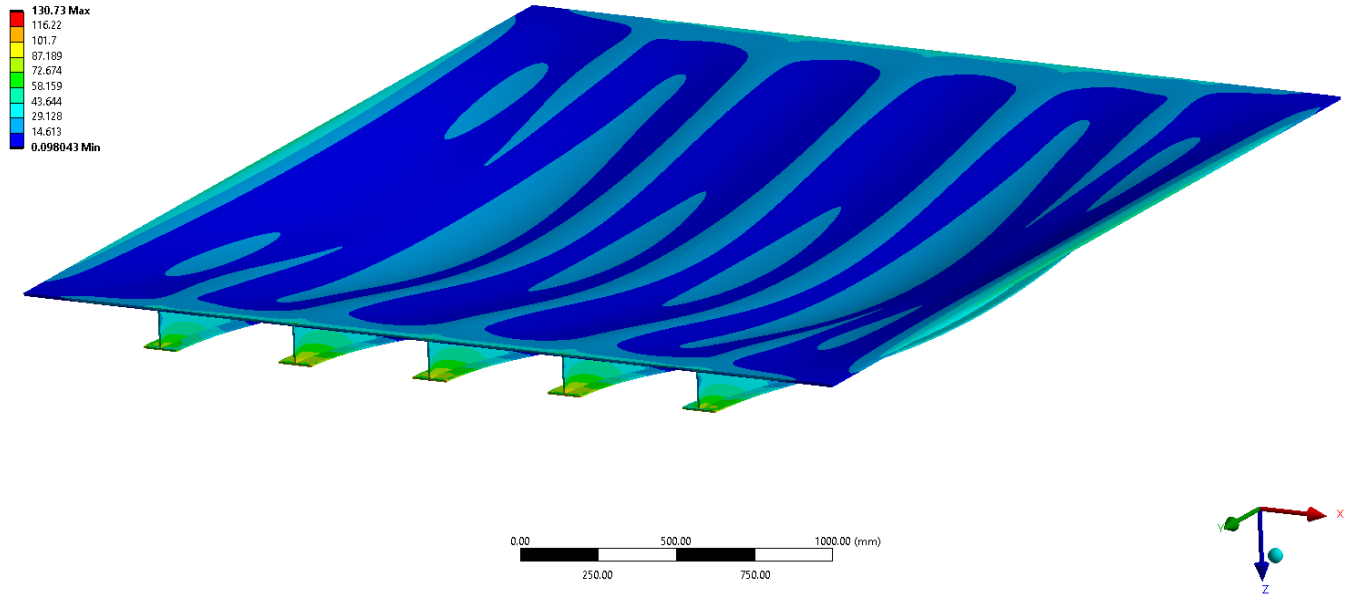


Figure 5-3 Equivalent (Von-Mises) stress for the initial design.

A pressure load of 0.02471 MPa was applied as the loading condition, representing the minimum scantling requirements for the primary structure within the ship's parallel middle body (Lloyd's Register, 2024). The initial static structural analysis revealed a maximum equivalent (von-Mises) stress of 130.73 MPa and an average stress of 18.827 MPa, as depicted in Figure 4. Furthermore, the structure's total deformation under this loading condition was also analysed, resulting in a maximum total deformation of 2.1165 mm and an average deformation of 0.9293 mm, as presented in Figure 5-5.

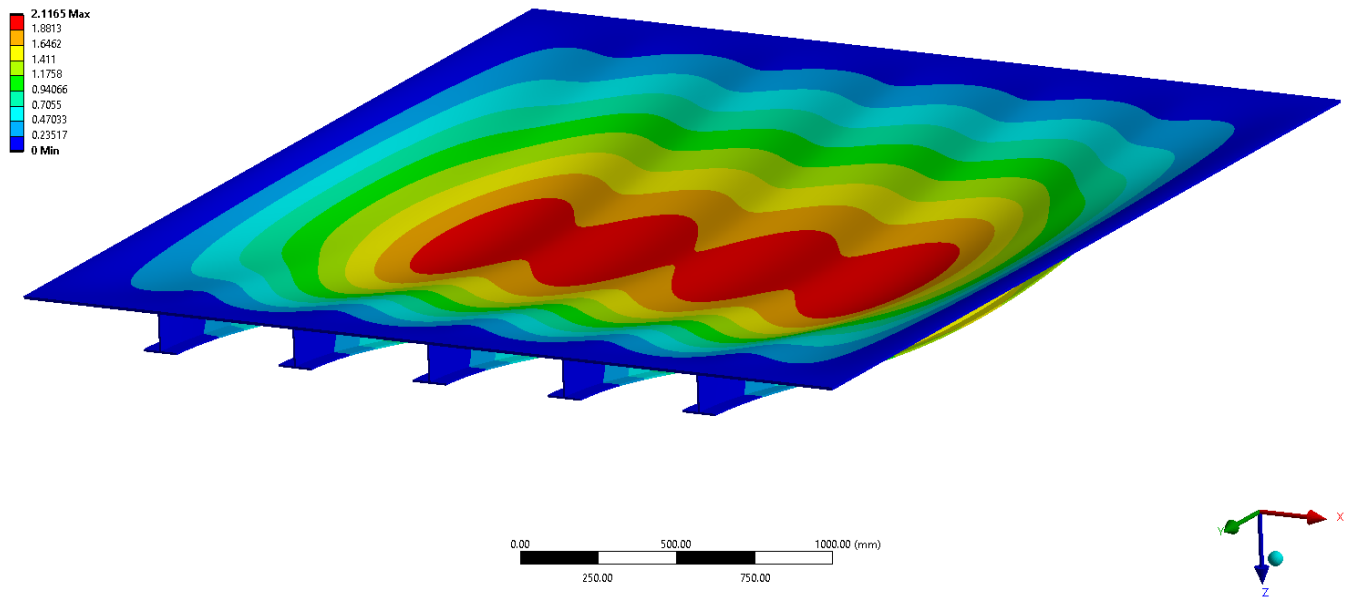


Figure 5-4 Total deformation for the initial design.

5.2.4 Optimisation Strategy

Optimising a stiffened panel involves balancing multiple objectives, particularly minimising the overall structural mass and reducing the web height, which directly affects the welding path during block assembly (R. Zhang et al., 2025). The goal of the multi-objective optimisation approach is to identify an optimal trade-off that considers all relevant performance criteria to achieve a well-rounded design solution. A schematic representation of the optimisation process is illustrated in Figure 5-6.

The MOGA method, a variant based on the widely adopted NSGA-II (Non-dominated Sorting Genetic Algorithm-II) architecture, was chosen for its proven capability to handle multiple conflicting objectives and nonlinear structural constraints simultaneously, aiming to approximate the true Pareto-optimal set (Pareto front) of non-dominated solutions across the design space (S. H. Shin et al., 2006). A key advantage of MOO algorithms like MOGA is their ability to identify a set of Pareto

optimal solutions (W. H. Chen et al., 2025), also known as the Pareto front, within a single simulation run (Cong et al., 2025). This set of compromise solutions allows designers to evaluate the trade-offs between objectives, such as balancing structural weight minimisation and reducing manufacturing effort often related to welding length (Sekulski, 2010). However, complex engineering problems, particularly those requiring computationally expensive simulations like Finite Element Analysis (FEA) for structural evaluation, can lead to prolonged computation times when directly integrated within iterative optimisation loops (L. Sun & Wang, 2011).

To address this, the optimisation methodology employed a robust framework combining Design of Experiments (DoE), Response Surface Methodology (RSM) and a Multi-Objective Genetic Algorithm (MOGA) as illustrated in Figure 5-6. A Central Composite Design was utilised to systematically generate the input data for the optimisation process (Cong et al., 2025). RSM is a mathematical and statistical tool used to construct predictive models or surrogate models that describe the relationship between input variables and system responses (objective functions and constraints) based on a set of design experiments (Myers et al., 2016). Once the input and output parameters are defined, Response Surface Methodology (RSM) is employed to construct a predictive model that describes the relationship between the design variables and the objective functions (Guerra et al., 2024).

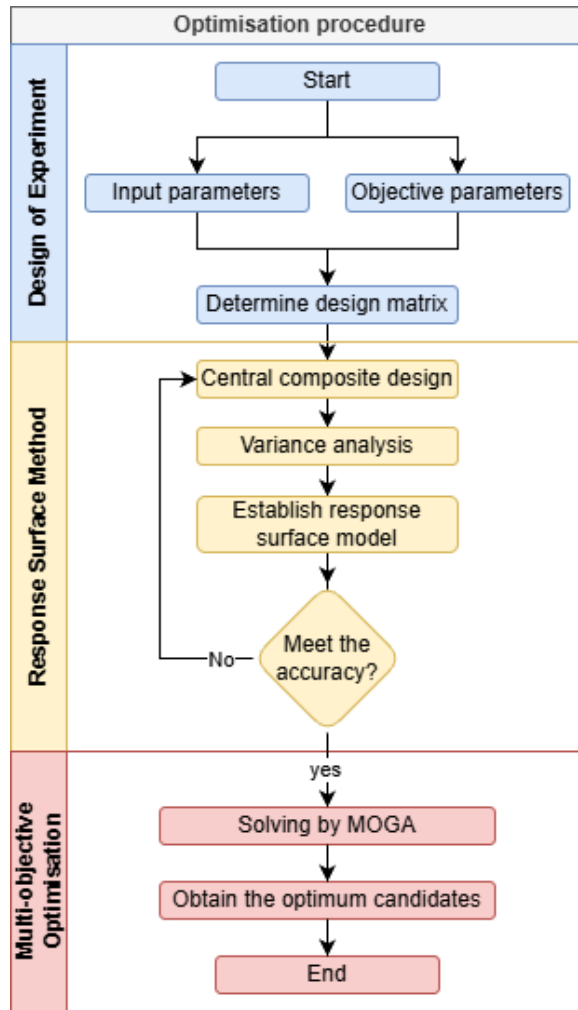


Figure 5-5 A diagrammatic illustration of the optimisation procedure.

The study aims to minimise two objectives, geometry mass and web stiffener height, which correspond to critical performance parameters. The optimisation is subject to several strict constraints, requiring the equivalent stress to be less than or equal to 175 MPa and a total deformation to be less than or equal to 10 mm. The MOGA method, a variant of the NSGA-II algorithm, was selected for its ability to handle multiple conflicting objectives and constraints to find a global optimum. The algorithm was configured to generate an initial population of 5,000 samples and run

for a maximum of 20 iterations, with 1,000 samples per iteration. The optimisation process successfully converged after 16 iterations and 16,444 evaluations, indicating that a stable and optimal solution was found. For the Response Surface Methodology (RSM) validation, a central composite design was used to generate a sample size of 27 design points. This approach ensured that the samples were uniformly distributed across the design space, providing a comprehensive and reliable basis for building the surrogate model and validating its accuracy.

The current optimisation framework primarily relies on a static analysis under a simplified uniformly distributed load. While this approach is effective for demonstrating the core methodology, it is a simplification of the complex loading conditions a ship structure experience. The model's primary limitation is the lack of a dynamic load analysis to account for wave-induced vibrations and sloshing effects, which can introduce cyclic stresses and fatigue issues. Despite these simplifications, our approach is scientifically grounded and valuable for a number of reasons. Static load analysis often serves as a key reference for fulfilling basic classification rules in the conceptual design phase. The primary purpose of our study was to showcase the feasibility and effectiveness of our optimisation method in reducing weight and welding, and the use of a static load allowed us to isolate these effects.

5.2.5 Optimisation Variable, Objective and Constraint

To ensure the practical applicability and manufacturability of the optimisation results, our framework uses discrete, commercially available and manufacturable

values for all design variables. The plate thickness is selected from a predefined list of standard plate thicknesses used in shipbuilding: $t \in \{4, 6, 8, 10, 12, 14\}$ mm. In addition, the stiffener profiles are chosen from a database of standard T-bars specified in shipbuilding including stiffener height (web plate, h) with a range of 70 mm to 140 mm, and stiffener flange (face plate, b) ranging from 50 mm to 140 mm. This approach ensures that the optimised design consists of components that can be readily procured and installed in a shipyard.

The optimisation problem was formulated with specific objectives and constraints: the optimisation objectives were to minimise geometry mass and minimise web plate height, which is directly correlated with the welding length during the assembly process inside the double-bottom structure. The objective function for minimising the geometry mass of the stiffened plate can be mathematically modelled based on the sum of the mass of the flat plate and the mass of the stiffeners. The objective function to be minimised is the total geometry mass (m_{total}), expressed as a function of the design variables:

$$\text{Minimise } m_{total}(t, h, b, t_w, t_f) \quad (5.2)$$

The mass of each component is calculated by multiplying its volume by the material density (ρ), where the volume is the product of its cross-sectional area and its length. Assuming the stiffeners run along the length (L_y) of the plate, the total geometry mass can be defined by the following formula:

$$m_{total} = (\rho \times L_x \times L_y \times t) + (n \times A \times L_y \times \rho) \quad (5.3)$$

This equation can be simplified as:

$$m_{total} = \rho \times L_y \times (L_x \times t + n \times A) \quad (5.4)$$

Where m_{total} is total geometry mass, ρ is density of the mild steel material, which is 7800 kg/m³, L_x is the width of the plate, which is 2935 mm, L_y is the length of the plate, which is 3450 mm, t is the plate thickness, n is the number of stiffeners, and A is the cross-sectional area of a single stiffener, which is calculated from the dimensions of the stiffener's web and flange, as shown in the cross-section diagram (Table 1). The cross-sectional area of the stiffener can be calculated using the formula:

$$A(h, b, t_w, t_f) = (h \times t_w) + (b \times t_f) \quad (5.5)$$

As stated in the study's objectives, minimising this height is directly correlated with reducing the welding length required during the assembly process inside the double-bottom structure. Based on the optimisation objectives explicitly stated in the study, the mathematical model for minimising stiffener height, or web height, is defined by the objective function:

$$\text{Minimise } f(h) \quad (5.6)$$

where the function $f(h)$ is simply the stiffener height itself:

$$f(h)=h \quad (5.7)$$

The optimisation process is subject to a set of constraints that ensure the design is both safe and manufacturable. The structural strength constraints include requirements for limiting maximum stress and deformation (Putra et al., 2019). In this

research constraints are based on Lloyd's Register Rules and Classification Standards, ensuring the structure can withstand operational loads (Lloyd's Register, 2024).

- Von Mises Stress: The von Mises stress (σ_v) at any point must not exceed the allowable material yield strength (σ_y), considering a safety factor (γ_s):

$$\sigma_v \leq \frac{\sigma_y}{\gamma_s} \quad (5.8)$$

- Combined Stress (According to LR Rules): The combined stress for hull vertical bending (σ) within 0.4L amidship. must not exceed the permissible limit given by LR rules, which is;

$$\sigma = \frac{175}{k_L} \text{ N/mm}^2 \quad (5.9)$$

Here, k_L is equal to 1 for the specified minimum yield stress, so an equivalent stress of ≤ 175 MPa is used. Another important LR rule is that a minimum plate thickness of ≥ 6 mm, including a corrosion margin, is used for the base plate. These rules provide criteria for evaluating the structural integrity of individual components as well as the overall ship (Raikunen et al., 2019).

5.2.6 Welding Length and Operational Constraints

In this study, welding length and welding operational time is a critical factor in the overall objective function. To model this, we have moved beyond a simple correlation

between stiffener web height and welding path length (Wahidi et al., 2023). The total welding length (L_{total}) for the stiffened plate is calculated using the following formula:

$$L_{total} = N_s \times (2 \times L_s) + N_{ends} \times (2 \times h) \quad (5.10)$$

where:

- N_s is the number of stiffeners.
- h is the height of the stiffener's web.
- L_s is the length of the stiffener.
- N_{ends} is the number of stiffener ends that require welding.

The total welding length is a primary driver of welding time. The relationship is not simply a linear one, as it depends on several factors, but a longer total welding length will always require more time. This relationship is defined by the welding travel speed in which the simulation use welding speed of 6.7 mm/s (Sá de Sousa et al., 2021), which is the rate at which the welding arc moves along the joint.

The basic formula to calculate the **arc time**, the actual time the welder is welding, is:

$$T_{arc} = \frac{L_{total}}{S_{travel}} \text{ minutes} \quad (5.11)$$

where:

- T_{arc} is the total arc time.
- L_{total} is the total welding length.
- S_{travel} is the welding travel speed (e.g., in mm/min).

However, total welding time (T_{total}) is not just the arc time. It also includes non-productive activities that take up a significant portion of the work hours, such as:

- Joint preparation
- Preheating
- Positioning and tacking
- Changing electrodes or wire spools
- Cleaning welds (e.g., slag removal)
- Inspection and rework

This is accounted for by the operating factor, or duty cycle, which is the percentage of total work time that a welder is actively welding. The operating factor value is typically between 20% and 50% for manual welding (Mason, 2022). The manufacturing operation duration was evaluated in terms of labour man-hours (*MH*), modelled as a function of the structural steel weight reduction achieved through the multi-objective optimisation. In shipbuilding production planning, structural fabrication effort is widely benchmarked using the metric of man-hours per metric ton (*MH/t*) (Storch, 1995)

The main factors contributing to welding man-hour cost in a ship production are welding volume and welding operational time. A higher welding volume directly translates to more time spent by skilled labour on welding tasks. Similarly, increased welding operational time, which encompasses all activities from preparation to finishing, raises the total man-hours required for project completion. Therefore, optimising both welding volume and operational time is crucial for reducing man-hour costs and improving overall project efficiency.

5.3 Results

The optimisation process successfully identified a set of design configurations that balance the trade-offs between structural weight and web height. The web height represents the welding path during welding process inside the double bottom. The results are presented in the form of a Pareto front, which illustrates the non-dominated solutions obtained using the Multi-Objective Genetic Algorithm (MOGA) and Response Surface Methodology (RSM).

5.3.1 The quality of response surface

Figure 5-7 shows a side-by-side comparison of the normalised values measured at the best design point and the predicted values from the response surface model. This visual concordance is critical for validating the model's predictive capability. The precision of the response surface model is quantitatively assessed through the coefficient of determination (R^2). For this study, the R^2 values demonstrated a high degree of model accuracy: the coefficients of determination for geometry mass and total deformation maximum were both recorded at 99%, while the R^2 value for the maximum equivalent stress was 98%. Such high R^2 values clearly show that the response surface model effectively represents the connections between the design factors and the results (maximum equivalent stress and geometry mass). Specifically, an R^2 value close to 100% means that almost all the differences in the data can be explained by the model, giving us great confidence in its ability to accurately find the best designs that reduce both weight and welding needs in tight shipbuilding areas. This strong correlation validates the model's utility as a reliable tool for structural optimisation in this challenging environment.

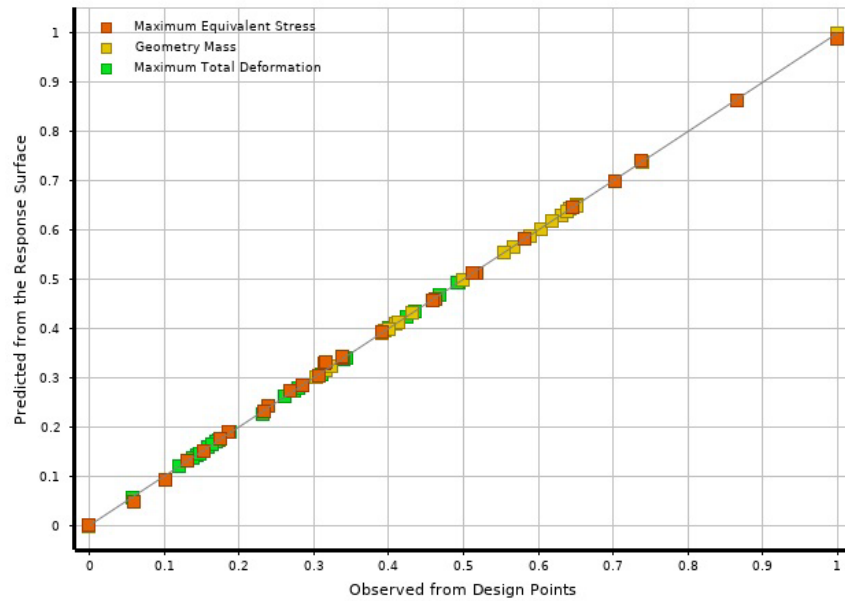


Figure 5-6 The response surface goodness of normalised predicted and observed values.

5.3.2 Sensitivity analysis

Figure 5-8 presents the results of a Local Sensitivity Analysis, providing critical insights into the influence of individual input design parameters on the key output performance metrics: Maximum Equivalent Stress and Geometry Mass. Local sensitivity quantifies the percentage change in an output parameter for a given percentage change in an input parameter, typically around a specific design point (e.g., the optimal or initial design) (Hosseini Imeni et al., 2022). A local sensitivity analysis was performed to determine the principal design elements affecting geometrical mass and maximum equivalent stress, specifically examining the influence of structural thickness configuration (plate thickness, web thickness, flange thickness) and flange width.

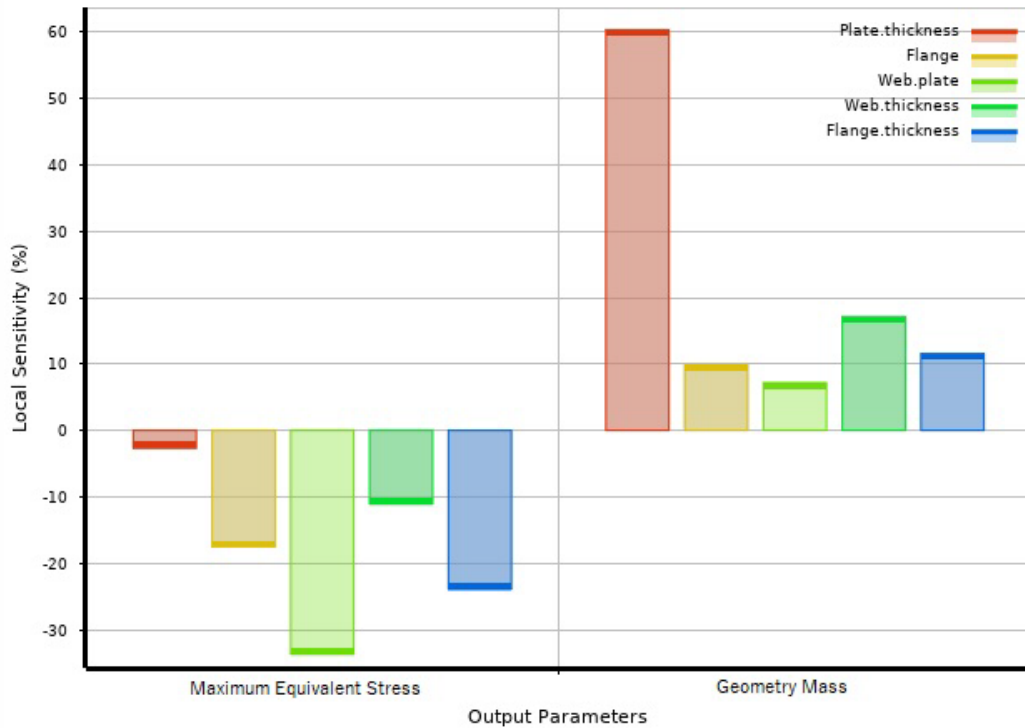


Figure 5-7 Local Sensitivity Analysis of Output Parameters to Design Variables.

For Maximum Equivalent Stress, all analysed input parameters demonstrate a negative sensitivity, indicating that an increase in any of these dimensions leads to a reduction in the maximum equivalent stress. Notably, web plate (light green bar) shows the most significant negative sensitivity, approximately -32%. This implies that even a small increase in web plate dimension can substantially decrease the maximum stress within the structure. Other parameters such as flange thickness (blue bar, around -23%) and flange (gold bar, around -17%) also show considerable negative influence on stress. This correlation is expected, as increasing structural dimensions generally enhances stiffness and load-bearing capacity, thereby lowering stress concentrations.

Conversely, for Geometry Mass, all input parameters display a positive sensitivity, meaning an increase in any dimension will result in an increase in the total

mass of the component. Plate thickness (red bar) is mainly the most sensitive parameter, demonstrating an approximate +60% sensitivity. This highlights its dominant role in contributing to the overall geometry mass. Other parameters like web thickness (dark green bar, around +17%) also significantly impact mass, while flange (gold bar, around +10%), flange thickness (blue bar, around +11%), and web plate (light green bar, around +7%) show relatively lower but still positive sensitivities.

These sensitivity results are crucial for the multi-objective optimisation process, as they identify which design variables have the most profound impact on the desired outcomes. For instance, while increasing web plate effectively reduces stress, it also contributes to mass. The analysis underscores the inherent conflicts between minimising mass and stress, guiding engineers in making informed design compromises on the Pareto front.

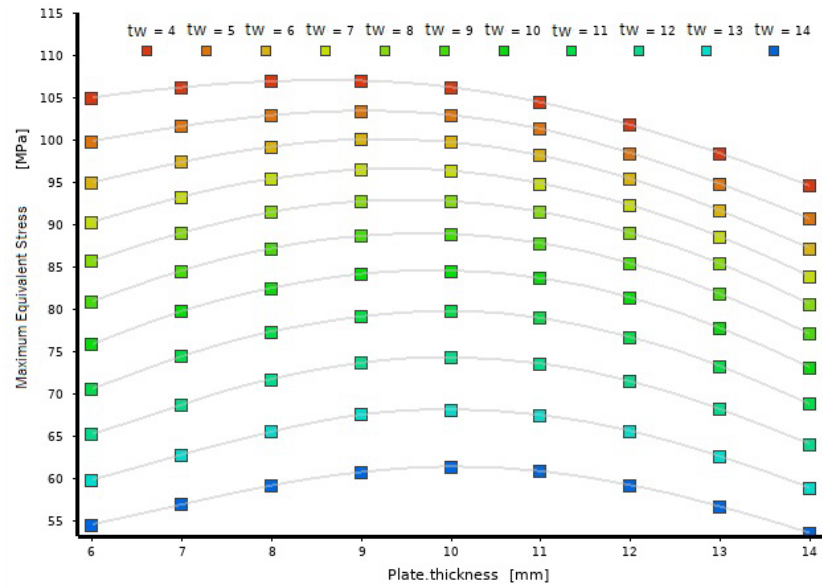
5.3.2.1 Effect of plate thickness and web thickness

This section details the individual and combined effects of plate thickness and web thickness on the structural performance of the stiffened plate, specifically focusing on the Maximum Equivalent Stress and Geometry Mass.

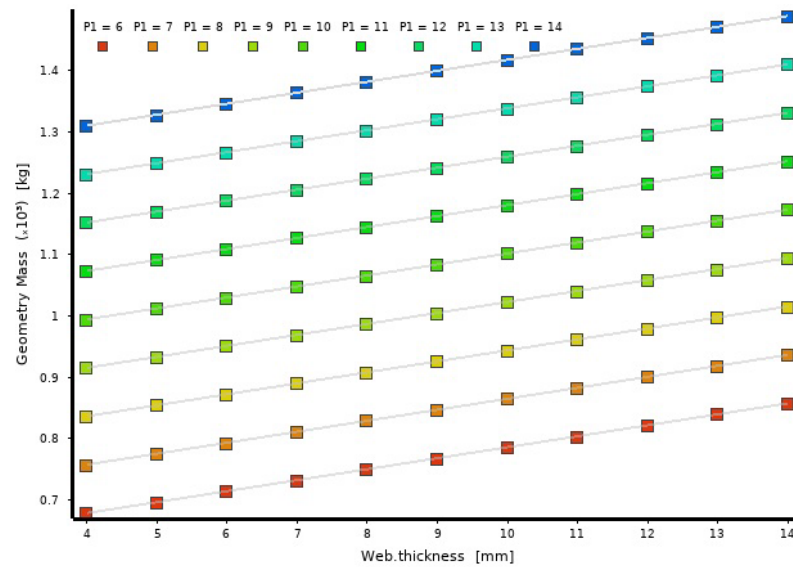
Figure 5-9a presents the Response Chart for Maximum Equivalent Stress, illustrating how maximum stress varies with plate thickness on the x-axis and for different fixed values of web thickness (t_w). The chart clearly indicates that for any given web thickness, an increase in plate thickness consistently leads to a reduction in the Maximum Equivalent Stress. Similarly, observing the trend across different series (representing increasing web thickness), it is evident that larger web thicknesses (t_w) also contribute to lower maximum stress levels. This relationship is critical for

ensuring structural integrity, as both parameters enhance the stiffness and load-bearing capacity of the plate.

Conversely, Figure 5-9b displays the Response Chart for Geometry Mass, detailing the influence of web thickness on the x-axis and various fixed values of plate thickness (PI) presented as a distinct colour series. This chart demonstrates a direct and almost linear relationship: as web thickness increases, the Geometry Mass invariably increases for all plate thickness values. More notably, the chart highlights the overwhelming influence of plate thickness (PI) on geometry mass. A change in plate thickness results in a much larger incremental change in mass compared to a similar change in web thickness. This is visually evident by the significant vertical separation between the series lines, where higher plate thicknesses (e.g., $PI = 14$ mm) correspond to substantially greater masses than lower plate thicknesses (e.g., $PI = 6$ mm) across the entire range of web thickness.



(a)



(b)

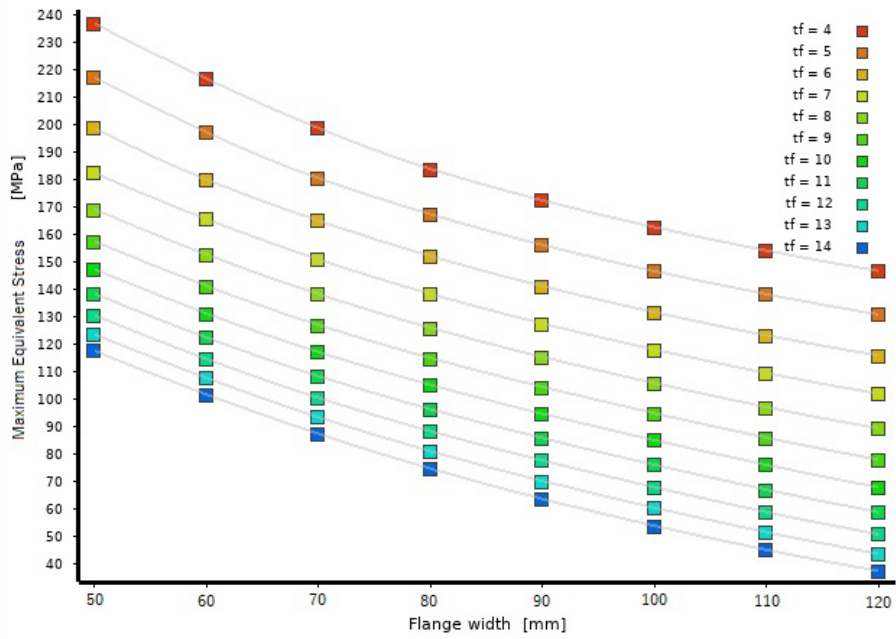
Figure 5-8 Response Charts Illustrating the Effect of Plate and Web Thickness on (a) Maximum Equivalent Stress and (b) Geometry Mass.

In comparison, while both plate thickness and web thickness effectively reduce the Maximum Equivalent Stress, they concurrently lead to an increase in Geometry

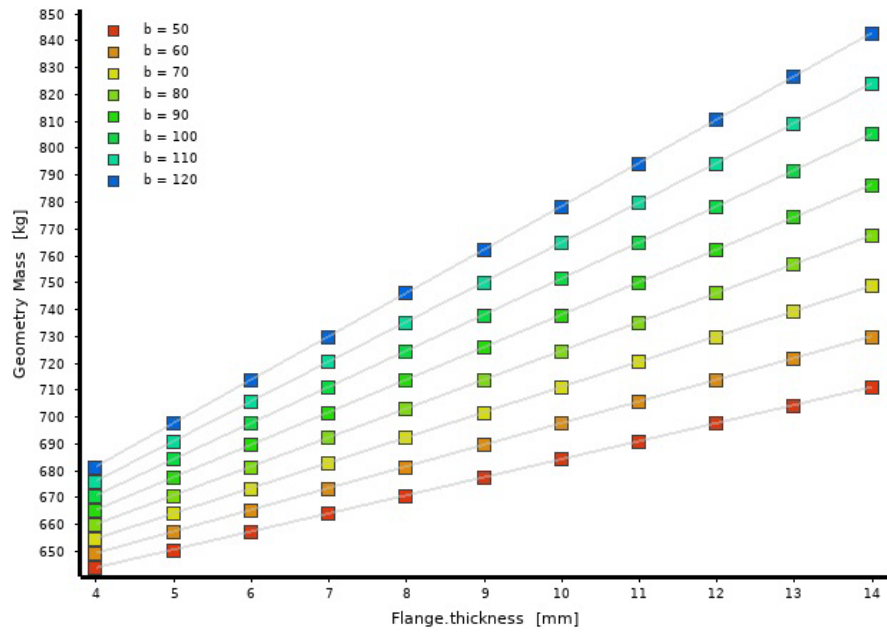
Mass. This contradiction highlights the fundamental conflict in multi-objective optimisation aiming to minimise both stress and mass. The analysis reveals that plate thickness (*PI*) is the most dominant factor influencing geometry mass, making it a critical variable for weight reduction. However, reducing plate thickness also has a significant adverse effect on stress levels. Therefore, these trade-offs must be carefully considered. For instance, a slight increase in web thickness might offer a pathway to manage stress increases with a relatively lower penalty on total mass, especially when attempting to optimise the plate thickness for mass minimisation while adhering to the maximum allowable stress constraint of 175 MPa. These response charts are essential tools for navigating such design compromises and selecting an optimal solution that balances structural performance with material efficiency.

5.3.2.2 Effect of flange width and flange thickness

This section analyses the influence of flange width and flange thickness on the structural performance of the stiffened plate, specifically concerning the Maximum Equivalent Stress and Geometry Mass.



(a)



(b)

Figure 5-9 Response Charts Illustrating the Effect of Flange Width and Flange Thickness on (a) Maximum Equivalent Stress and (b) Geometry Mass.

Figure 5-10a presents the response chart for Maximum Equivalent Stress, illustrating its variation with flange width on the x-axis, for different fixed values of flange thickness (t_f) shown as a distinct colour series. The chart clearly indicates that for any given flange thickness, an increase in flange width consistently leads to a reduction in the Maximum Equivalent Stress. This is evident as the lines generally slope downwards from left to right. Similarly, observing the trend across different series, it is apparent that larger flange thicknesses (t_f) also contribute to lower maximum stress levels, as the lower-lying lines correspond to thicker flanges. This inverse relationship is fundamental for enhancing structural integrity, as both parameters increase the cross-sectional area and moment of inertia, thereby distributing stress more effectively.

Conversely, Figure 5-10b displays the response chart for Geometry Mass, detailing the influence of flange thickness on the x-axis and various fixed values of flange width (b) displayed as a distinct colour series. This chart demonstrates a direct and generally linear relationship: as flange thickness increases, the Geometry Mass consistently increases for all flange width values. Furthermore, the chart highlights the significant influence of flange width (b) on geometry mass. For a given flange thickness, increasing the flange width leads to a substantial increase in mass, as indicated by the clear vertical separation between the series lines. Higher flange widths correspond to greater masses across the entire range of flange thickness.

In comparison, while both flange width and flange thickness effectively reduce the Maximum Equivalent Stress, they concurrently lead to an increase in Geometry Mass. This again underscores the inherent conflict in multi-objective optimisation

aiming to minimise both stress and mass. The analysis reveals that both flange width and flange thickness have a significant positive impact on geometry mass, requiring careful consideration during the optimisation process. Engineers must strategically balance the need for stress reduction with the imperative for mass minimisation. These response charts are vital tools for navigating such design compromises, enabling the selection of an optimal solution that balances structural performance with material efficiency while adhering to all design constraints.

5.3.3 The optimisation results

The multi-objective optimisation, utilising MOGA, converged after 16444 evaluations as illustrated in Figure 5-11, identifying optimal design candidates. The chart illustrates the history of a minimisation process for Geometry Mass. The horizontal axis represents the Number of Points, with values ranging from 0 to approximately 1.6×10^4 . The vertical axis shows the Geometry Mass in kilograms, ranging from 0 to 1.5×10^3 kg. The red line with square markers, represents the evolution of the geometry mass during the optimisation process. Initially, the mass values are highly scattered, fluctuating significantly between approximately 0.6×10^3 kg and 1.4×10^3 kg. As the number of points increases, the spread of the data points begins to decrease, indicating that the optimisation algorithm is converging. Beyond 1.0×10^4 points, the mass values settle into a more stable range, with most points clustering around 0.7×10^3 kg. The blue dashed line, labelled 'Expected Target Value' of 0 kg, is the baseline that the optimisation is aiming for to minimise the objective function.

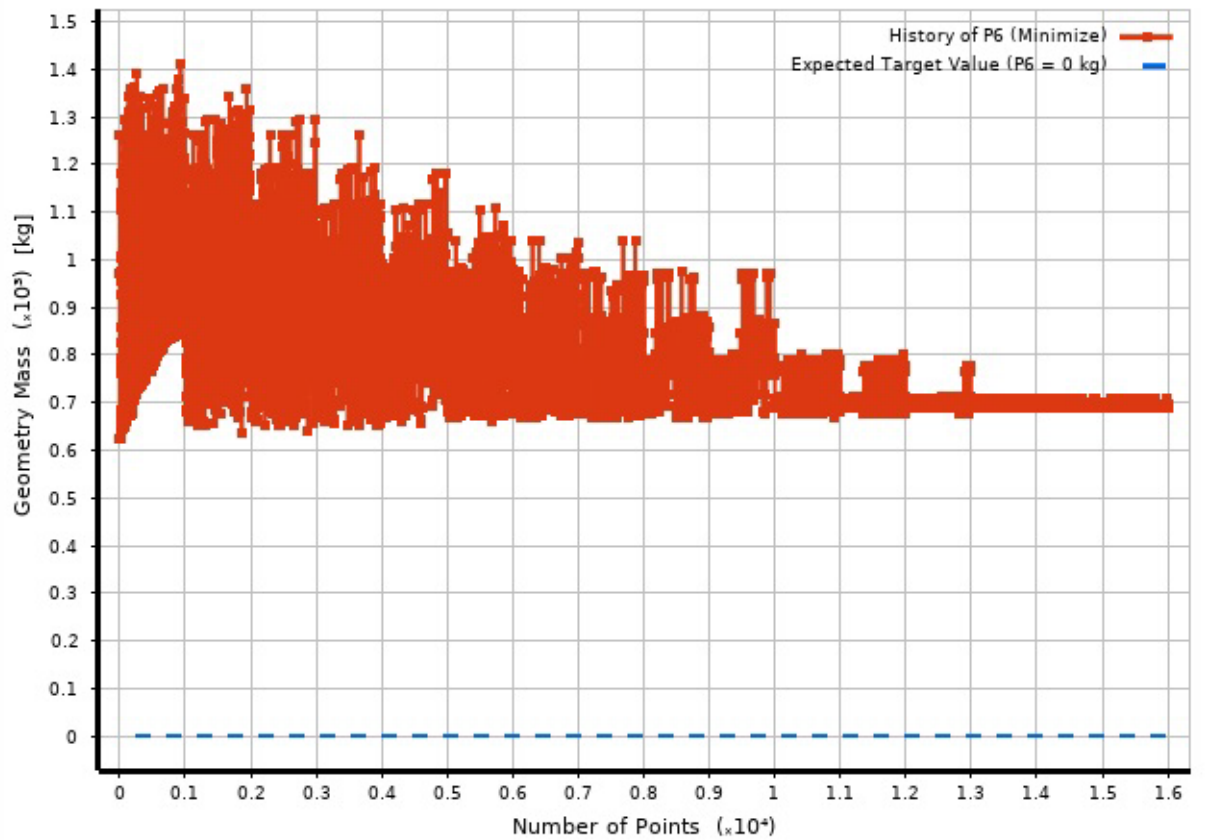


Figure 5-10. The convergence of the optimisation process from an initial state

Table 5-2 Comparison between the original design with the optimum design.

Parameter	Initial Design	Optimum Design	FEA validation
Base plate thickness	10 mm	6 mm	6 mm
Stiffener height / Web plate	130 mm	95 mm	95 mm
Web plate thickness	7 mm	8 mm	8 mm
Stiffener flange / face plate	120 mm	90 mm	90 mm
Flange thickness	7 mm	11 mm	11 mm
Geometry mass	1018.7 kg	697.06 kg	697.06 kg
Maximum equivalent stress	130.73 MPa	174.92 MPa	173.36 MPa
Max deflection	2.12 mm	5.0962 mm	5.0916 mm

The optimisation process successfully yielded a design that significantly reduced both geometry mass and web plate height while strictly adhering to the specified constraints. Table 5-2 provides a comparison of the initial and optimised design parameters. The optimised design achieved a substantial 32% reduction in geometry mass, from 1018.7 kg to 697.06 kg. Simultaneously, the web plate height was successfully minimised from 130 mm to 95 mm. This reduction in web plate height is directly beneficial as it decreases 27% of the required welding length during the double-bottom block assembly, addressing a key challenge in confined shipbuilding spaces. Critically, the maximum equivalent stress of the optimised design is 173.36 MPa, which complies with the specified constraint of 175 MPa according to classification rules. While maximum deflection increased from 2.12 mm to 5.0915 mm, it remains within acceptable limits for the given structural type.

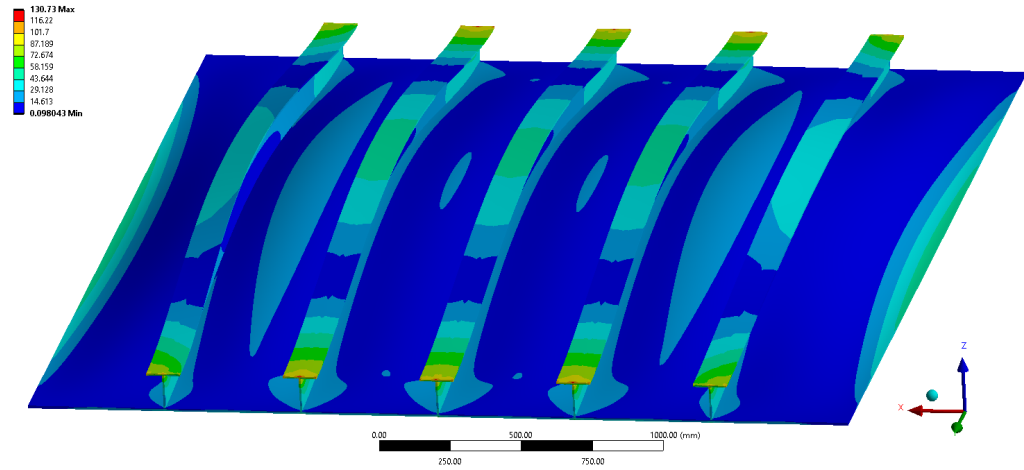
This optimised design offers significant advantages over the previously reviewed studies. Compared to these studies, maintaining the number of stiffeners avoids an increase in material handling. Additionally, the reduction in web plate height decreases welding volume, which leads to a lower overall production cost, thereby directly addressing the background issues prevalent in block assembly within confined spaces. Furthermore, the use of manufacturable plate thickness values ensures that the optimised design is practical and adheres to industrial market standards.

5.3.4 Comparative Analysis of Stress and Deformation

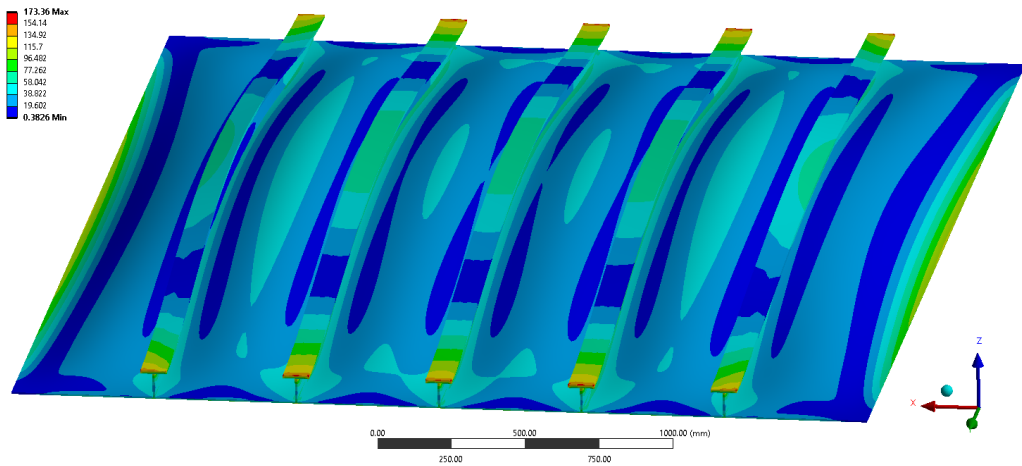
The equivalent (von-Mises) stress distribution for both the initial and optimised stiffened plate designs is presented in Figure 5-12a and Figure 5-12b, respectively. For the initial design, the maximum equivalent stress was calculated as 130.73 MPa. The

stress contour for this design indicates relatively localised regions of higher stress (represented by yellow and orange hues) primarily concentrated around the stiffener connections and plate edges, with larger areas of the plate exhibiting lower stress levels (blue and cyan).

In contrast, the optimised design exhibits a maximum equivalent stress of 173.16 MPa. While this value is higher than that of the initial design, it remains compliant with the stipulated class regulation constraint of 175 MPa. Visual analysis of the optimised design's stress contour reveals a more widespread and efficient distribution of stress across the plate surface. The material appears to be utilised more effectively, with stress levels more evenly distributed (indicated by broader areas of green and yellow hues) rather than being concentrated in highly localised hotspots as seen in the initial design. This increase in stress utilisation across the structure is a characteristic outcome of mass optimisation, where material is strategically removed, leading to the remaining material bearing higher stresses that are nonetheless within the allowable limits. This demonstrates that the optimisation successfully achieved its objective of reducing weight by more effectively leveraging the structural capacity of the material, pushing stress levels closer to the design limit without exceeding it.



(a)



(b)

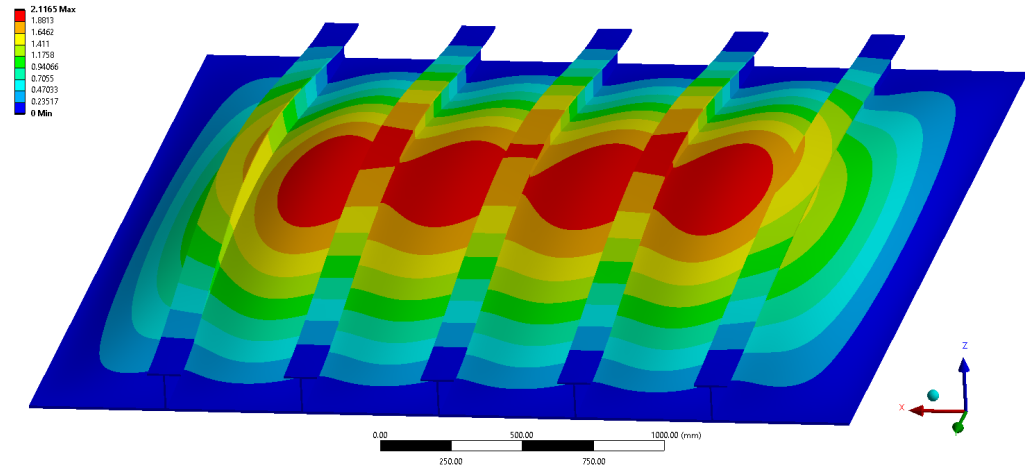
Figure 5-11. Equivalent (von-Mises) Stress Distribution. (a) Initial design, showing a maximum stress of 130.73 MPa and localised high-stress regions. (b) Optimised design, demonstrating a maximum stress of 173.16 MPa and a more widespread stress utilisation across the plate, adhering to the design constraint.

The total deformation distribution for the initial and optimised stiffened plate designs is presented in Figure 5-13a and Figure 5-13b, respectively. In the initial design, the maximum total deformation was observed to be 2.1165 mm. The contour

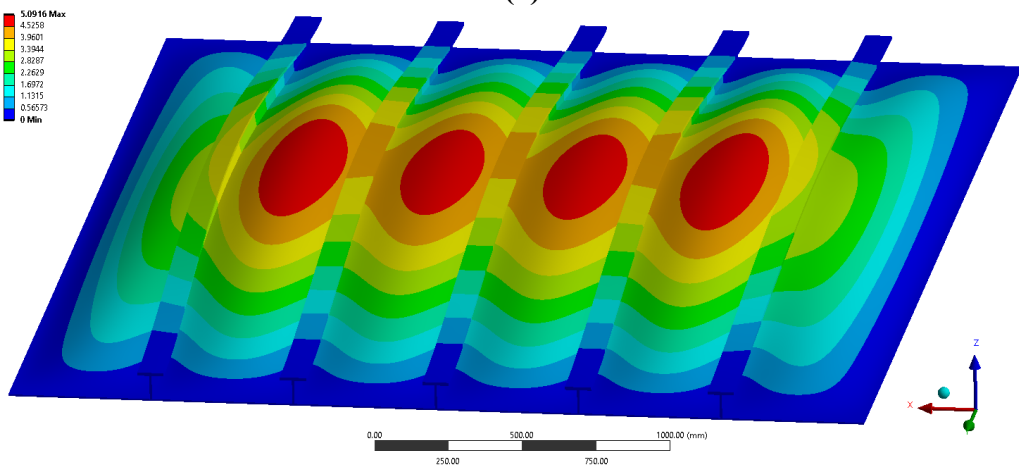
plot (Figure 5-13a) reveals distinct elliptical regions of higher deformation (indicated by red and orange hues) occurring primarily between the longitudinal stiffeners, which is characteristic of plate bending under distributed load. Deformation gradually diminishes towards the stiffener lines and plate boundaries.

In contrast, the optimised design exhibits a maximum total deformation of 5.0916 mm. While this represents a notable increase compared to the initial design's deformation, the overall pattern of deformation between the stiffeners remains similar, although with wider and more intense areas of increased displacement. This increase in flexibility is an expected consequence of the mass minimisation objective, as the removal of structural material naturally leads to a less rigid structure. Despite this increase, it is crucial to note that this deflection generally remains within the allowable limits specified by classification rules (e.g., often a constraint of 10 mm for maximum deflection in such structures), thereby preserving the structural integrity and functionality of the component. The ability to accommodate a higher level of deformation while significantly reducing mass underscores the efficiency achieved by the optimised design.

A recognised boundary condition limitation of this structural optimisation is the reliance on fully clamped edges along the plate perimeter and stiffener boundaries. While this provides a well-defined and reproducible structural baseline for local stress and scantling optimisation under Lloyd's Register rules, evaluating alternative boundary conditions (such as simply supported edges or multi-bay continuous panel models under combined in-plane and lateral loads) remains an important direction for future research.



(a)



(b)

Figure 5-12. Total Deformation Distribution for (a) the initial stiffened plate design and (b) the optimised design. While the initial design exhibits a maximum deformation of 2.1165 mm, the optimised, lighter design demonstrates an increased maximum deformation of 5.0916 mm, indicating a more flexible structure resulting from efficient material reduction within acceptable deflection limits.

5.3.5 Comparison results of optimised design and recent studies

To more rigorously validate the effectiveness of our optimisation framework, we conducted a comparative analysis with a similar study from the literature. We selected the work of (Putra et al., 2019) as a benchmark, as their research also focuses on the optimisation of a ship's stiffened plate using the same geometric configuration. However, their approach utilises a different methodology (a hybrid genetic algorithm) with a different optimisation output (variable number of stiffeners).

A side-by-side comparison of the results is presented in Table 5-3. When comparing the designs, a critical finding emerges regarding manufacturability and commercial viability. While the Published Article design presents an impressive geometry mass of 651.5 kg, it does so with a base plate thickness of 5.4 mm. This dimension is not a standard thickness available commercially, potentially increasing production time and cost due to custom manufacturing. In contrast, our Optimum Design utilises a 6 mm base plate, a readily available and cost-effective thickness, making it a more practical choice for commercial application. Furthermore, the Published Article design achieves its mass by increasing the number of stiffeners from 5 to 6, a change that would inevitably lead to greater handling and operational costs due to the added complexity and labour of positioning and welding an extra stiffener. Lastly, the mechanical performance of the Published Article design presents a significant concern. Its maximum deflection of 9.34 mm is nearly double the 5.4 mm base plate thickness, indicating a very flexible structure. Our Optimum Design, while experiencing greater deflection than the initial design, maintains a more reasonable deflection of 5.0916 mm, which is below the thickness of its own base plate and well

within an acceptable range for structural integrity. This highlights the superior balance of our Optimum Design, which offers substantial mass and time savings without sacrificing practicality or structural stability.

Table 5-3 Comparison of Key Parameters for Initial, Optimum, and Published Designs.

Parameter	Initial Design	Optimum Design	Published article
Base plate thickness	10 mm	6 mm	5.4 mm
Number of stiffeners	5	5	6
Stiffener height / Web plate	130 mm	95 mm	130 mm
Web plate thickness	7 mm	8 mm	7 mm
Stiffener flange / face plate	120 mm	90 mm	50 & 120 mm
Flange thickness	7 mm	11 mm	7 mm
Geometry mass	1018.7 kg	697.06 kg	651.5 kg
Maximum equivalent stress	130.73 MPa	173.36 MPa	134.7 MPa
Maximum deflection	2.12 mm	5.0916 mm	9.34 mm

Table 5-4 shows a clear advantage of the Optimised Design in terms of safety and efficiency, particularly for high-risk, confined spaces. Our research found that the Optimised Design led to a significant 27% decrease in welding volume during the block assembly process. This reduction in welding volume directly translates to a shorter time workers are exposed to the hazardous conditions within a confined space, thereby improving safety. While the Reviewed Article design also resulted in a lighter structure, it did so with a 20% increase in weld volume, which would have the opposite effect on safety by prolonging time exposure. This finding highlights a crucial benefit

of our optimised design that goes beyond material and cost savings, directly contributing to a safer manufacturing environment.

Table 5-4 Comparison of Welding Length Results for Initial, Optimum, and Published Designs.

Process	Item	Initial design	Optimised design	Reviewed article
Joining stiffener with base plate during panel assembly (open space)	Number of stiffeners	5	5	6
	Stiffener Length (mm)	3450	3450	3450
	Both side weld	2	2	2
	Weld length ℓ (mm)	34500	34500	41400
	ℓ +margin 5% (mm)	36225	36225	43470
	Weld length gap (mm)		0	7245
	Percentage difference		0%	20%
Joining stiffener with transverse web floor during block assembly (confined space)	Stiffener Height (mm)	130	95	130
	Both side + both end	4	4	4
	Weld length ℓ (mm)	2600	1900	3120
	ℓ +margin 5% (mm)	2730	1995	3276
	Weld length gap (mm)		-735	546
	Percentage difference		-27%	20%

Table 5-5 provides a detailed analysis of welding and operational times across three designs: the Initial Design, the Optimised Design, and the Existing Studies (Putra et al., 2019). The data highlights the significant efficiency gains achieved by the Optimised Design while also revealing the trade-offs of the Published Article design.

For the panel assembly process, both the Initial and Optimised designs exhibit the same welding parameters and total welding time (5406.72 s). However, the Optimised Design achieves a substantial reduction in operational time, leading to an

11% decrease in total time with operation. This is due to a reduction in weight, showcasing a key benefit of the optimisation.

The block assembly process, which takes place in a confined space, is where the benefits of the Optimised Design are most pronounced. By reducing the stiffener height from 130 mm to 95 mm, the total weld length is reduced by 27% (2730 mm to 1995 mm), resulting in a corresponding 27% decrease in total welding volume. This leads to a substantial 35% reduction in total time with operation compared to the Initial Design. In contrast, the Published Article design shows a 20% increase in welding time and a 6% increase in total time.

Overall, the Optimised Design demonstrates a remarkable 13% reduction in total process time compared to the Initial Design. This finding confirms the effectiveness of the optimisation in reducing both material mass and production time, resulting in significant cost and efficiency benefits. The Published Article, despite its own merits, results in a 6% increase in overall time, indicating that it does not provide the same level of time efficiency as the Optimised Design.

Table 5-5 Comparative Analysis of Welding and Operational Times for Initial, Optimised, and Existing Study Designs

Process	Item	Initial design	Optimised design	Existing studies
Joining stiffener with base plate during panel assembly (open space)	Total Weld length (mm)	36225	36225	43470
	Welding time (s)	5406.72	5406.72	6488.06
	Welding position	Down hand	Down hand	Down hand
	Position factor	1	1	1
	Total time (s)	5406.72	5406.72	6488.06
	Weight	1018.7	697.06	651.5
Operation time	Weight factor	1	0.68	0.64
	Operation time*	50%	34%	32%

Process	Item	Initial design	Optimised design	Existing studies
	Total time +operation (s)	8110.07	7256.53	8562.75
	Time gap		-853.55	452.67
	Percentage		-11%	6%
Joining stiffener with transverse web floor during block assembly (confined space)	Total Weld length (mm)	2730	1995	3276
	Welding time (s)	407.46	297.76	488.96
	Welding position	Vertical	Vertical	Vertical
	Position factor	1.5	1.5	1.5
	Total time (s)	611.2	446.6	733.4
	Weight (kg)	1018.7	697.06	651.5
	Weight factor	1	0.68	0.64
Operation time	Operation time*	50%	34%	32%
	Total time +operation (s)	916.79	599.45	967.96
	Time gap		-317.34	51.17
	Percentage		-35%	6%
Overall process	Total time (s)	9026.87	7855.98	9530.71
	Time gap		-1170.89	503.85
	Percentage		-13%	6%

Note: * Operation time was calculated as a function of weight, using the weight ratio from the optimisation results and in accordance with practical application.

The findings of this comparison confirm that our methodology is not only effective but also provides a more efficient and innovative solution for the design of ship double bottom structures than existing approaches in the field.

5.4 Discussion

This section presents a comprehensive discussion of the structural optimisation framework developed for enhancing shipbuilding processes. The analysis focuses on evaluating the framework's performance against conventional design methodologies and reviewed studies, as well as elucidating the significant practical and economic benefits derived from the optimised design. Specifically, this discussion will detail the comparative advantages of the proposed solution and examine the crucial role of weld

length reduction in improving productivity and safety within the constrained environments of ship double-bottom assemblies.

5.4.1 Comparative Analysis with a Published Study

The proposed structural optimisation framework presents significant advantages over existing design practices, particularly concerning the fabrication of stiffened plates within confined shipbuilding spaces (Lee et al., 2011). A detailed comparison of the optimised design with findings from reviewed studies underscores the practical and economic benefits achieved as shown in Table 5-6.

Table 5-6 Comparison of findings from reviewed studies with the proposed optimisation.

No	Parameter	Reviewed studies	Proposed design
1.	Plate thickness variable	Any numbers	Manufacturable value
2	Constraint	Unknown	Class Regulation Standard
3	Number of stiffeners	Increase	Same
4	Web plate height	Same	Decrease
5	Material handling	More	Less
6	Welding process	More	Less
7	Geometry mass	Minimised	Minimised
8	Production cost	Higher	Lower

A key distinction of the present work lies in the plate thickness variability. While previous studies may have explored a wide range of numerical values for plate thickness (Putra et al., 2019), this research explicitly incorporated manufacturable values using industrial market standards. This pragmatic approach ensures that the optimised designs are not merely theoretically superior but are also directly applicable in a shipyard environment, aligning with real-world material availability and fabrication constraints (Ehlers et al., 2015).

Furthermore, a critical aspect addressed in this study is the integration of explicit constraints based on Class Regulation Standard (Lloyd's Register). In contrast to some reviewed studies where the specific constraints applied might remain unknown or less rigorously defined, our methodology ensures that the optimised structure complies with established maritime safety regulations, such as maintaining the maximum equivalent stress below 175 MPa and adhering to minimum plate thickness requirements. This regulatory compliance is paramount for the certification and operational safety of the vessel (Lloyd's Register, 2024).

Regarding the number of stiffeners, previous optimisation approaches sometimes indicated an increase to achieve certain performance gains. However, the proposed design maintains a comparable number of stiffeners to the initial model. This is crucial for simplifying the production process, as not increasing the number of stiffeners tends to lead to less material handling and less welding process during stiffener plate production. This directly mitigates one of the challenges associated with complex structures in confined spaces.

Quantitatively, the optimisation achieved a remarkable 32% reduction in geometry mass. This substantial weight saving, contributes significantly to improving fuel efficiency, reducing material costs, and potentially increasing payload capacity (D. H. Kim & Paik, 2017). Collectively, these improvements directly translate to a lower production cost for the optimised structure compared to previous methods.

A substantial contribution of this optimisation is the targeted decrease in web plate height. Unlike studies where this parameter might remain constant or not be a primary focus, its reduction in the proposed design directly translates into a significant

27% decrease in welding volume. This, in turn, leads to a lower overall production cost, directly addressing the inherent background issues of extensive welding and material handling prevalent in double-bottom block assembly within confined spaces. This advancement is particularly beneficial for facilitating the integration of automated systems. The integration of robotic welding systems in ship double-bottom structures offers considerable potential to enhance productivity by reducing reliance on human labour and mitigating the overall production duration, thereby identifying opportunities for cost reduction (Wahidi et al., 2023). However, significant challenges and limitations persist, particularly when dealing with complex geometries in the confined spaces of the marine industry, which must be addressed to fully exploit the potential of robotic automation. In response to these challenges, research has been dedicated to developing specialised solutions, such as the mobile robotic system designed for working within double-hulled structures (Lee, 2013). Therefore, this optimisation concept serves as a foundational support system, providing a structurally verified and streamlined design that can make the subsequent automated production process more efficient and cost-effective by reducing variables such as the required welding length and material handling.

While our optimisation framework incorporates a manufacturable range of values for plate and stiffener dimensions, we recognise that this is a generalised approach. The design variables were deliberately chosen to use manufacturable values that meet industrial market standards, rather than continuous numbers. This ensures our results are directly applicable and can be procured from steel suppliers. However, a specific shipyard's production environment may impose additional, more granular

limitations. For instance, a shipyard might specialise in a certain welding technique requiring a minimum gap between stiffeners, or its lifting equipment may have a weight limit for pre-fabricated blocks. Our current model does not account for these highly specific constraints. While our optimised design is theoretically manufacturable, a more tailored optimisation would be necessary to fully align with a particular shipyard's capabilities. Future work will focus on integrating such process-specific constraints into the model, bridging the gap between theoretical optimisation and practical, shipyard-specific production.

5.4.2 The Benefits of Reducing Weld Length in Confined Spaces

Reducing weld length in confined spaces can significantly improve safety and reduce welding defect rates by minimising exposure duration to hazards and mitigating welder fatigue and ergonomic strain (Lowe et al., 2001; Okumus et al., 2023; Pribadi & Shinoda, 2025; Weman, 2012). A comprehensive analysis of how reduced weld length contributes to enhanced safety and improved welding defect rates is provided in Table 5-7.

Table 5-7 Analysis of the benefits of reducing weld length in confined spaces.

Category	Specific Benefit	How Reduced Weld Length Helps	Related Citations
Safety Improvements	Reduced Static Loading and Awkward Postures	Reduces time in strained positions, decreasing muscle effort and the risk of musculoskeletal disorders.	(Arifin et al., 2023; Lowe et al., 2001; Okumus et al., 2023)
	Decreased Muscle Fatigue	Shortens continuous welding, reducing the onset and severity of fatigue.	(Arifin et al., 2023; Lowe et al., 2001; Okumus et al., 2023; Pribadi & Shinoda, 2025)
	Reduced Exposure to Fumes and Gases	Shortens welding duration, lowering the welder's overall dose of toxic substances.	(Bowler et al., 2007; Okumus et al., 2023; Persoons et al., 2014; K. Weman, 2012)

Category	Specific Benefit	How Reduced Weld Length Helps	Related Citations
	Lower Risk of Accidents	Lessens fatigue, helping welders maintain concentration and physical control to prevent accidents.	(Okumus et al., 2023)
	Mitigation of Performance Drop Due to Fatigue	Shorter welds lessen fatigue, allowing welders to sustain focus and precision.	(Okumus et al., 2023; Pribadi & Shinoda, 2025)
Improved Welding Defect Rates	Enhanced Stability and Precision	Less fatigue enables welders to maintain the stability needed for high-quality welds.	(Lowe et al., 2001; Okumus et al., 2023; Pribadi & Shinoda, 2025)
	Reduced Spatter and Improved Operational Stability	A less-fatigued welder can better maintain optimal welding parameters for a stable operation.	(Ding et al., 2025)

5.4.2.1 Safety Improvements

Welding tasks, particularly manual operations involving thicker, heavier, or larger parts, lead to longer welding times, increased static loading, and greater equipment weight (Weman, 2012). In confined spaces, welders are often forced into awkward, static postures, such as kneeling with a highly flexed trunk, which places considerable stress on the low back and shoulders (Arifin et al., 2023; Lowe et al., 2001). These postures contribute to musculoskeletal symptoms in the neck, shoulders, and low back (Lowe et al., 2001; Okumus et al., 2023). Reducing weld length means less time spent in these strained static positions, decreasing static muscle efforts and the risk of musculoskeletal disorders (Arifin et al., 2023; Okumus et al., 2023).

Muscle fatigue is a major concern in confined space welding (Lowe et al., 2001; Okumus et al., 2023; Pribadi & Shinoda, 2025). Studies show that measurable changes in muscle electromyography (EMG) and perceived discomfort occur even during short periods of static exertion (e.g., 2-3 minutes of welding) (Lowe et al., 2001). Prolonged static positions can lead to reduced blood supply to tendons, causing tiredness and strain (Arifin et al., 2023). Short-term fatigue, a daily occurrence from physically

demanding tasks, can manifest as mental exhaustion, lack of alertness, and general body fatigue (Okumus et al., 2023). Shorter weld lengths would directly translate to shorter continuous welding durations, thereby reducing the onset and severity of muscle fatigue (Lowe et al., 2001; Okumus et al., 2023).

Welders are exposed to fumes and gases, including ultraviolet radiation, and drops of molten metal (Weman, 2012). Welding fumes contain small solid particles of iron oxides and manganese oxides, with basic electrodes also releasing fluorides (Weman, 2012). Welding high-alloy and stainless steels releases chromium and nickel compounds, which are a cancer risk, while manganese can harm the nervous system (Weman, 2012). The amount of fume produced increases with welding current (Weman, 2012). The duration of welding directly influences a welder's internal dose of toxic metals like chromium, nickel, and manganese (Bowler et al., 2007; Persoons et al., 2014). Chronic low exposure to manganese, as observed in confined space welding, can lead to neurological disorders, including neuromotor and behavioural deficits (Bowler et al., 2007; Persoons et al., 2014). Reducing weld length directly shortens the duration of welding activity, consequently lowering the overall exposure to harmful fumes and gases (Okumus et al., 2023).

Fatigue is a significant contributor to human error, accidents, decreased efficiency, and higher error rates (Okumus et al., 2023). By reducing fatigue through shorter welding durations, welders can maintain better concentration and physical control. This mitigates the risk of human error and, subsequently, reduces the likelihood of accidents (Okumus et al., 2023).

While the current optimisation framework considers standard design regulations and material properties, a key limitation lies in the lack of constraints consistent with the actual manufacturing process. The optimisation results, while structurally efficient, do not explicitly account for critical factors such as welding space, welding posture, and the required fixture arrangements. These elements are fundamental to ensuring that the optimised design can be realistically fabricated. Future work will integrate these specific process-related constraints into the optimisation model. This will involve developing a computational model that simulates manufacturing operations, allowing the optimisation algorithm to not only seek the most structurally sound design but also one that is demonstrably manufacturable.

5.4.2.2 Improved Welding Defect Rates

Welders frequently experience a decline in performance because of fatigue (Pribadi & Shinoda, 2025). Short-term daily fatigue can lead to a substantial productivity loss (e.g., a 22.9% loss compared to a rested condition in a simulation study) (Okumus et al., 2023). Fatigue also negatively impacts judgment, efficiency, and productivity, leading to increased error rates and quality issues (Okumus et al., 2023). By reducing weld length, the shorter duration of welding can lessen fatigue, enabling welders to sustain higher performance, focus, and precision throughout the task, thereby contributing to fewer defects (Okumus et al., 2023; Pribadi & Shinoda, 2025).

Manual welding demands high skill and precision (Lowe et al., 2001; Okumus et al., 2023; Pribadi & Shinoda, 2025). While high-quality welds are achieved with a

slower, more deliberate travel speed for a given section (Pribadi & Shinoda, 2025), a shorter weld length inherently reduces the overall time required to complete the weld. This reduced overall duration, combined with less fatigue, helps the welder maintain the necessary stability and precision for the entire weld, leading to better quality and fewer defects.

Although reducing weld length does not change the rate of spatter generation, it reduces the total duration of spatter-producing activity for a specific weld. A lower welding speed can contribute to a more stable welding operation and reduce spatter (X. Ding et al., 2025). A less fatigued welder, resulting from shorter weld lengths, is more likely to maintain optimal welding parameters, leading to a more stable operation and potentially fewer defects such as spatter (X. Ding et al., 2025).

While the present study provides a numerical framework for optimising stiffened plate structures, a crucial next step for validating the results is through experimental testing and real-world shipyard trials. These trials could involve fabricating a small-scale prototype of the optimised structure to measure actual welding hours, assess the ease of assembly, and monitor for potential fabrication defects. Furthermore, a full-scale trial could be conducted in a real shipyard environment, where the optimised design is compared against a conventional design. The key performance indicators would include the reduction in welding time, a decrease in the weld defect rate, and an overall improvement in manufacturing efficiency. Such validation is essential to confirm that the theoretical benefits of the optimised design translate into tangible improvements in production metrics, thereby providing a more comprehensive and directly applicable solution for the shipbuilding industry. This work is part of our

future research agenda to ensure our models are not just theoretically sound but also practically viable.

Chapter 6. Kinematic Evaluation of Multi-Position Robotic Welding in Confined Ship Structures within a Design for Automation (DfA) Framework

6.1 Chapter Outline

This chapter details the systematic approach to Simulation and Implementation of Robotic Welding in Confined Shipbuilding Spaces to address this critical dependency. The primary objective is twofold: first, to develop a high-fidelity Virtual Prototyping Framework (VPF) of a double-bottom structure within the ABB RobotStudio environment; and second, to use this simulation to definitively validate the structure's practical compatibility with commercial robotic welding arms by performing comprehensive kinematic, accessibility, and path planning analyses. The resulting outcomes are then synthesised with the structural configuration to establish a robust 'Design for Automation' (DfA) framework.

Based on the operational bottlenecks identified in the assembly of these confined structures, this chapter aims to address the following research questions:

1. How do extreme spatial constraints (1200 mm height) affect the kinematic dexterity and reachability of an industrial robot during the welding of double-bottom stiffeners?
2. Which mounting configuration provides the most favourable trade-off between structural clearance and the ability to perform continuous bay-to-bay transitions?

3. How can a virtual prototyping framework effectively predict and mitigate collision risks and mechanical energy consumption in confined-space robotic operations?

The novelty of this chapter lies in its detailed collision analysis, which identifies the physical limitations of inverted and elevated robot configurations. Based on simulation findings, this paper argues that successful robotic integration requires a "Design for Automation" philosophy, specifically through stiffener structural optimisation. By adjusting stiffener profiles and heights, the robot's workspace can be expanded, ensuring collision-free transversal movement without the need for complex and heavy overhead gantry systems within the confined double-bottom space.

The remainder of this chapter is organised as follows: Section 6.2 reviews the current state of automation in shipbuilding and outlines key challenges. Section 6.3 details the methodology and the setup of the RobotStudio simulation environment. Section 6.4 presents the results of the kinematic, accessibility, and path generation analyses. Section 6.5 discusses the implications of the findings on logistics and efficiency. Finally, Section 6.6 provides the concluding remark and suggests avenues for future research.

6.2 Automation in Shipbuilding and Key Challenges

The shift toward automation in shipbuilding, as shown in Figure 2-15, is driven by the necessity to reduce manufacturing costs, improve consistency, and compete with high-volume international shipyards (Wahidi et al., 2024). Modern ship construction relies on the principle of sub-assembly, where large modules are fabricated in controlled environments before final erection.

6.2.1 Established Automation Trends

Significant progress has been made in automating the early and mid-stages of the shipbuilding process (Zheng, An, et al., 2022). These established trends primarily include:

- **Panel Line Automation:** Large-scale flat panel welding lines utilise gantry-type or rail-mounted welding machines, often integrating non-destructive testing (NDT) systems (L. Yang et al., 2021). These systems are highly efficient for repetitive, large-area welding, which accounts for a substantial portion of the ship's structure (Zheng, Xing, et al., 2022).
- **Sub-Assembly Robotics:** Robotics have been successfully applied to standardised units, such as T-bar stiffeners and small block assembly, where the working environment is relatively open and predictable (J. G. Shin & Sohn, 2000).

Digital Shipyard Concept: The use of advanced planning tools and simulation software is now standard practice for verifying assembly sequences, clash detection, and material flow, forming the foundation of the digital shipyard (Cil et al., 2022).

6.2.2 The Logistical and Operational Gap

Despite these advancements, automation penetration decreases sharply as the construction moves into the final assembly stage and highly constrained internal spaces (Zhou et al., 2021). The primary logistical gap lies in the transition from open-environment, predictable welding to confined-environment, variable welding. This gap is exacerbated by the trend toward optimised hull structures, which, while beneficial for hydrodynamics and material reduction, often introduce geometric

complexities that challenge standard robotic reach and movement (Wahidi et al., 2025).

6.2.3 Key Challenges to Automation in Confined Spaces

Automating welding tasks within tightly confined areas, such as the double-bottom, wing tanks, and engine room blocks, presents a multi-faceted set of technical and operational challenges that must be overcome before widespread adoption can occur (Wahidi et al., 2024):

- **Kinematic and Accessibility Constraints:** The geometric density of internal stiffeners and webs imposes severe restrictions on the robot's working envelope as illustrated in Figure 6-1. Access points are limited, often requiring the robot to manoeuvre its arm and torch assembly through narrow apertures (Wahidi et al., 2023). This leads to a high probability of singularities (robot joints aligning in a way that limits movement) and collisions with surrounding structure elements. Verifying reachability under strict positional and angular requirements is non-trivial and often impossible without high-fidelity simulation.



Figure 6-1 Representative environment of a ship's double-bottom confined space, illustrating the severe kinematic and accessibility constraints faced during assembly. The narrow manhole access (as seen in the lower compartment) dictates the maximum physical dimensions for robotic deployment, while the 1.2 m vertical clearance presents significant safety and ergonomic hazards for manual labour, necessitating a transition to automated welding solutions. (Note: This photograph was taken during a ship production supervision project conducted by the authors and the team from Institut Teknologi Sepuluh Nopember).

- **Safety and Ergonomics:** From a production logistics perspective, relying on manual welding in confined spaces carries inherent occupational risks, including poor ventilation, difficult access for rescue, and high ergonomic strain, leading to reduced productivity and inconsistent quality due to welder fatigue. As shown in Figure 6-1, the 1.2 m vertical clearance and restricted manhole access create a workspace where manual welding is both ergonomically inefficient and

operationally limited. Automation is the most direct method to eliminate these risks entirely (Wahidi et al., 2022).

- **Path Planning Complexity:** Generating a reliable, collision-free trajectory for thousands of linear and curvilinear weld seams inside a variable and constrained volume is computationally intensive (X. Chen et al., 2018). Traditional teach-pendant programming is impractical; thus, reliable off-line programming (OLP) systems, like RobotStudio, are required to interpret complex CAD geometry and automatically generate safe, optimised paths.

Therefore, the successful deployment of robotic welding in confined spaces depends on a rigorous, simulation-based methodology that can systematically address and overcome these kinematic and accessibility barriers, thereby providing the necessary assurance for industrial implementation.

6.3 Methodology

The methodology for this research is centred on a high-fidelity, simulation-driven validation approach to determine the practical manufacturability of a ship double-bottom structure using commercially available robotic welding systems (Wahidi et al., 2025). The overall process comprises four main phases: digital twin development, automated path planning, rigorous kinematic and accessibility analysis, and finally, DfA implementation.

6.3.1 Robotic Welding Simulation Workflow

The systematic approach of this study is illustrated in Figure 6-2, which outlines the logical progression from problem identification to final comparative analysis.

- **Identifying Issue and Literature Review:** The research began by identifying the operational constraints of robotic welding in ship double-bottom structures, supported by a comprehensive review of existing automation technologies in the maritime sector.
- **Modelling and Specification:** The 3D geometry of the ship's double-bottom block was developed to reflect actual confined space conditions. This was followed by a technical comparison of robot specifications to ensure the selection of an appropriate manipulator for the task.
- **Positioning and Teaching:** Various robot and welding positions were established within the virtual environment. Targets and welding instructions were then programmed into the system to define the operational paths.
- **Simulation and Analysis:** The simulation was executed to monitor performance (Rong, Xu, et al., 2018), followed by a comparative analysis of the different configurations to determine the most effective setup.

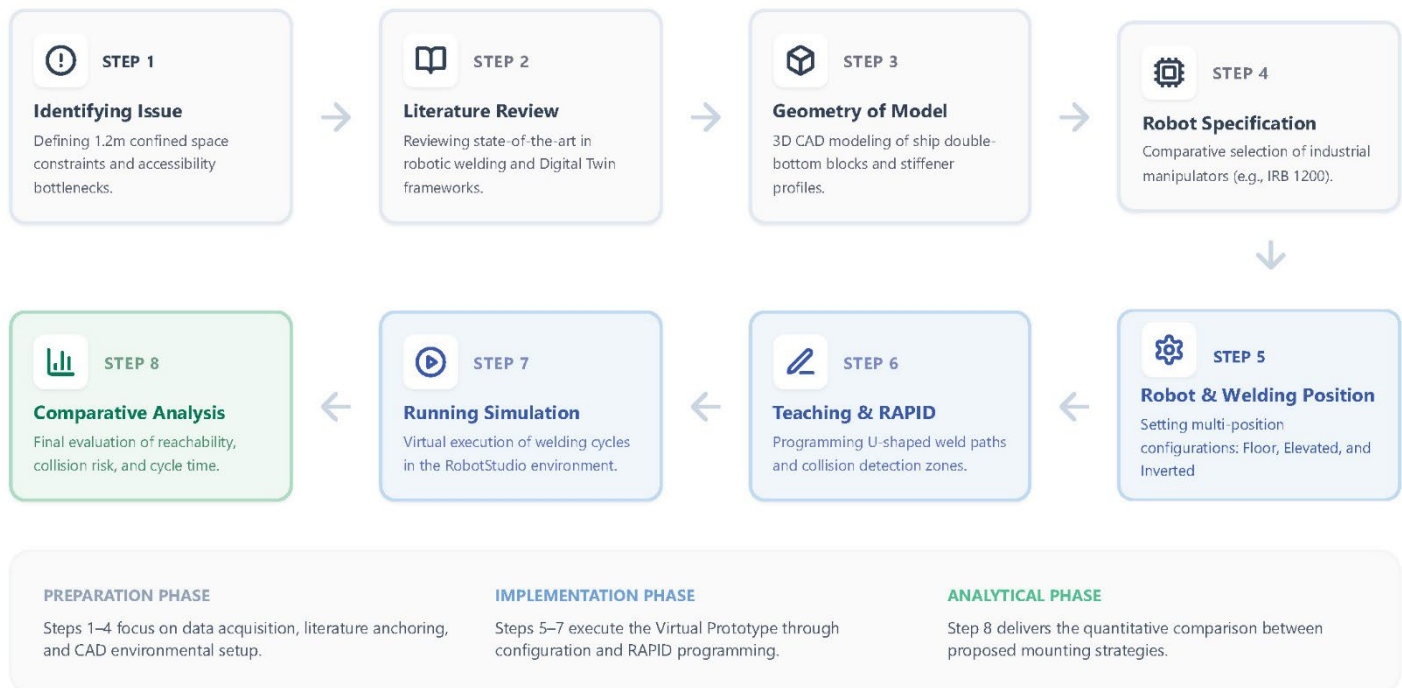


Figure 6-2 Methodological framework and project outline for robotic welding simulation.

6.3.2 Operational Context and Assembly Sequence

The simulation parameters were designed to replicate the actual ship block assembly sequence as illustrated in the project outline. The process begins with the open block stage, where welding is typically performed using a robotic welding gantry for maximum accessibility. Following the initial welds, the block is turned over and positioned onto the bottom shell, effectively creating a closed block.

This study focuses on the subsequent critical phase: robotic welding entering the enclosed space to complete internal joins. The primary task modelled in the Digital Twin Prototype (DTP) is the execution of the U-shaped welding line process, which connects longitudinal stiffeners to the bottom floor as shown in Figure 6-3. This

sequence defines the limited path planning requirements that the robot must navigate without structural interference.

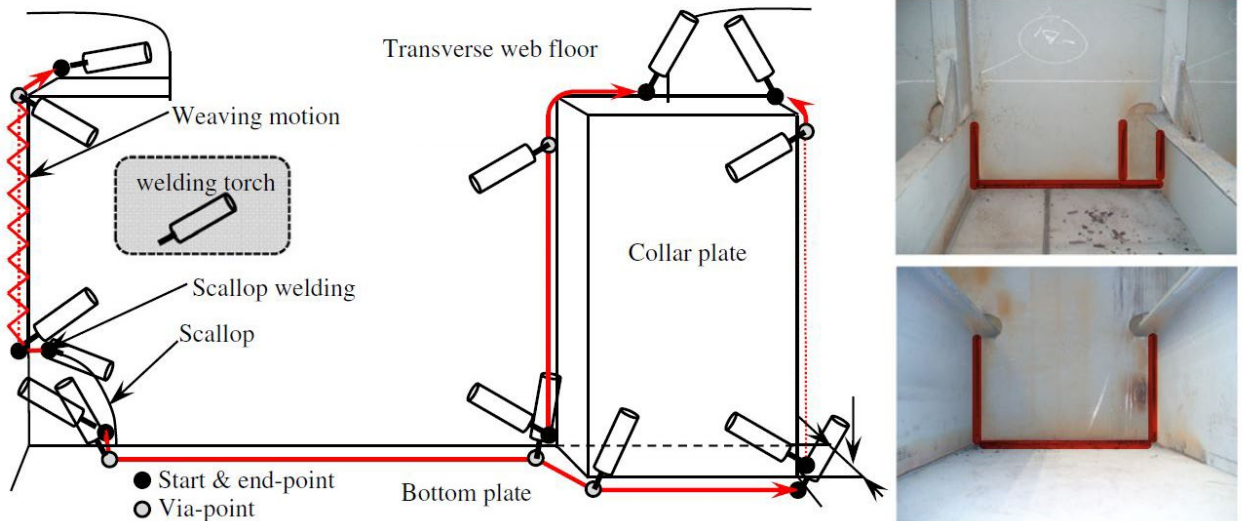


Figure 6-3 Identification of the target welding path: The typical U-shaped boundary formed by the intersection of the longitudinal stiffener and the bottom shell plate within a ship block compartment (Lee et al., 2011).

6.3.3 Robotic Manipulator Selection and Reachability Criteria

The selection of the robotic manipulator is primarily dictated by the arm reach specification relative to the dimensions of the ship's double-bottom compartment. As illustrated in Figure 6-4, a comparative analysis was conducted between two variants of the ABB IRB 1200: the IRB 1200-5/0.9 (right) with a 900 mm reach and the IRB 1200-7/0.7 (left) with a 700 mm reach. While both models share a compact footprint suitable for manhole entry, the simulation results demonstrate that the 0.9 m reach variant provides the necessary kinematic flexibility to cover the entire transversal span of the U-shaped welding line without repositioning the base. Conversely, the 0.7 m reach model exhibits significant accessibility limitations, particularly when navigating

the outer corners of the longitudinal stiffeners, thereby confirming that a minimum reach of 0.9 m is a critical criterion for ensuring full task coverage within the 1200 mm height structural constraint.

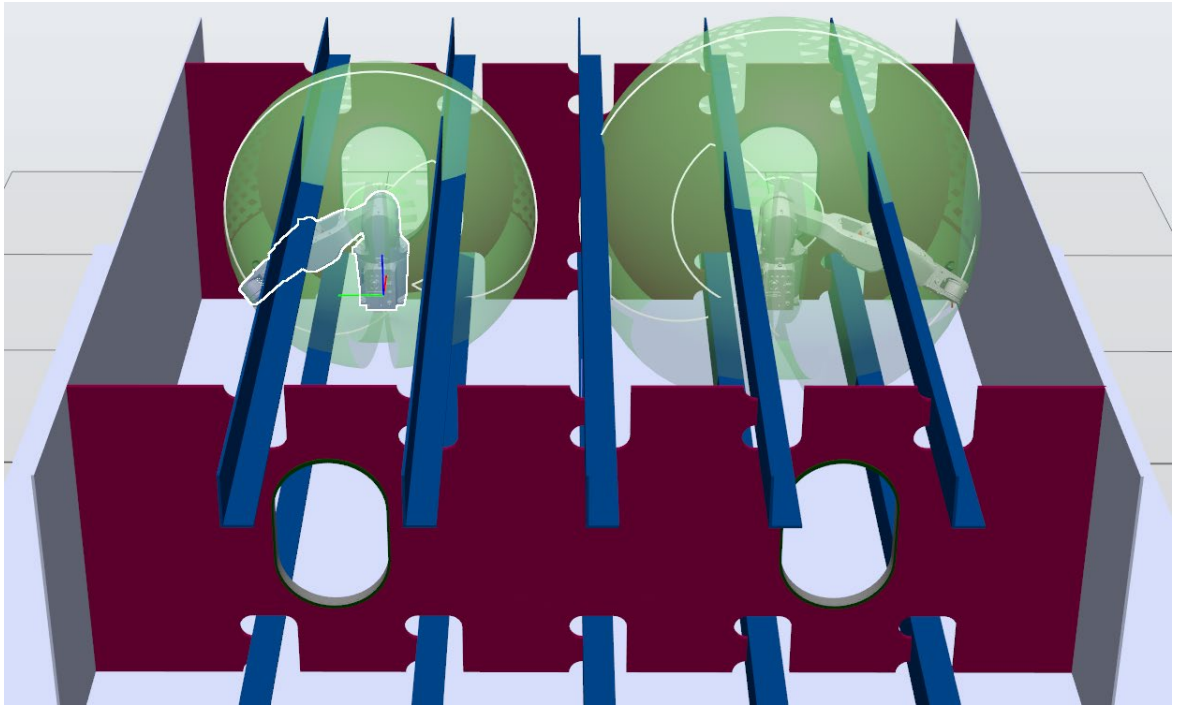


Figure 6-4 Comparative reachability analysis for robot specification selection: (left) IRB 1200 with 0.7 m reach showing limited workspace coverage; (right) IRB 1200 with 0.9 m reach demonstrating optimal access to the target welding seams.

The operational efficiency of the two models was further evaluated based on the required number of base positioning sequences. As demonstrated in Figure 6-4, the IRB 1200-5/0.9 (right) is capable of completing three consecutive U-shaped welding seams from a single base position. In contrast, the IRB 1200-7/0.7 (left) requires at least two separate base positions to complete the same task due to its restricted workspace. When extrapolated to the entire ship structure, which consists of hundreds of identical compartments, the necessity for frequent base relocation using the 0.7 m

variant would lead to a multi-fold increase in setup time and logistical complexity. Consequently, the IRB 1200-5/0.9 is identified as the optimal selection for this environment, as it significantly minimises non-productive time and streamlines the automated assembly process across the whole vessel.

6.3.4 Virtual Prototyping Framework

This study employs a Virtual Prototyping Framework approach, utilising a high-fidelity virtual environment to evaluate robotic performance before physical deployment (Tao et al., 2018). The DTP framework integrates the exact kinematic parameters of the ABB IRB 1200 industrial robot with the CAD geometry of a ship's double-bottom block. This digital representation allows for the precise calculation of joint limits, reachability, and potential collisions in a risk-free virtual testbed.

To facilitate a high-fidelity simulation, a Digital Twin Prototype (DTP) was constructed (Putranto et al., 2025). This virtual environment, as shown in Figure 6-5, replicates the complex internal geometry of two types of ship's double-bottom structure, including longitudinal stiffeners and transverse bulkheads with manhole openings. An ABB industrial robot was integrated into the structural model. The base of the robot was positioned atop the longitudinal stiffeners to evaluate transversal mobility and reachability within the bay compartments.

The environment was designed to simulate a restricted height of 1.2 meters, providing a rigorous testbed for detecting kinematic interference between the robot arm (specifically Axis 3) and the overhead structure. The developed simulation serves as a Digital Twin Prototype (DTP), functioning as a virtual validation to analyse

robotic reachability and collision avoidance in ultra-confined spaces where physical trial-and-error is economically and safety-prohibitive (Arifin et al., 2023).

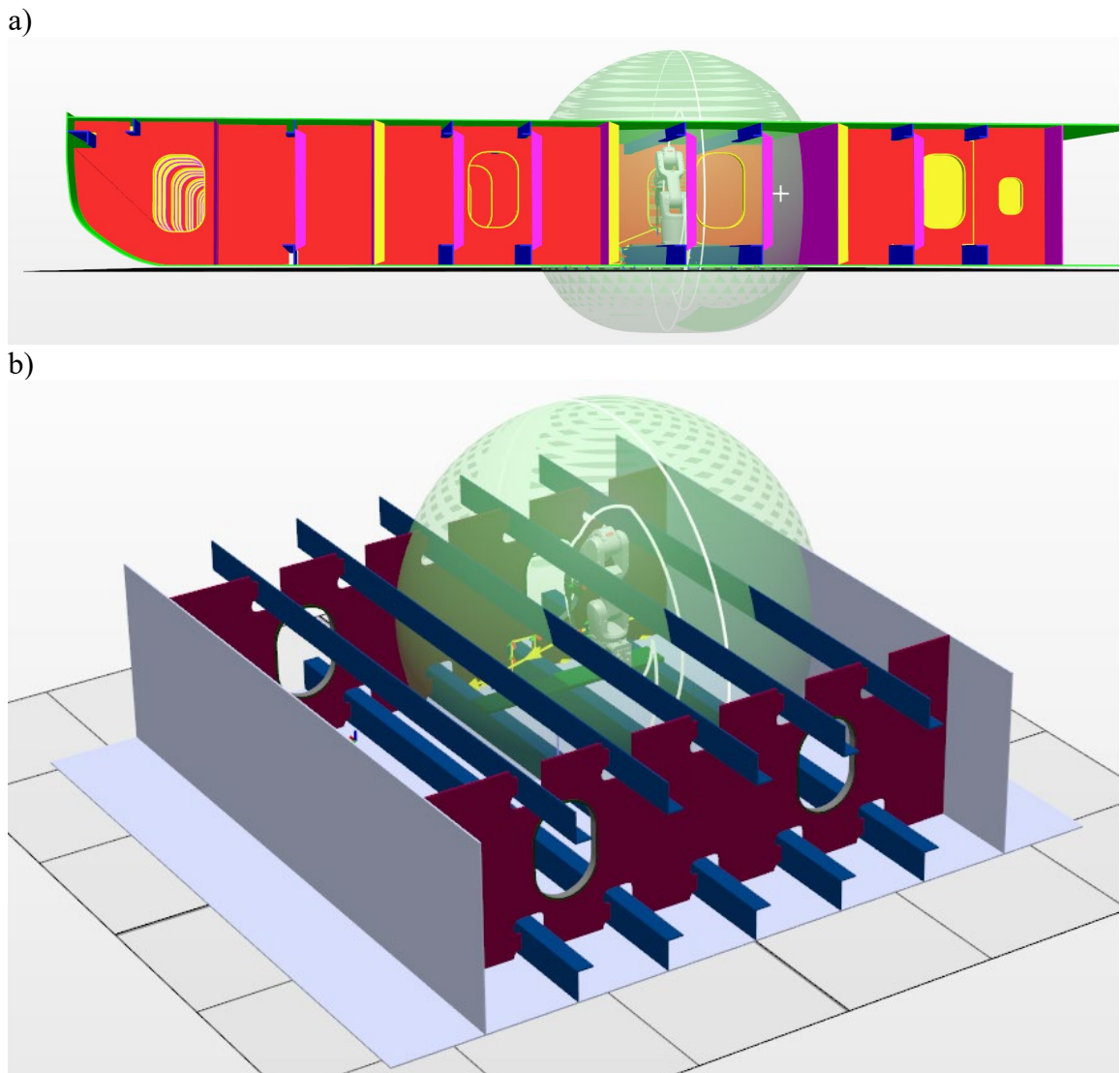


Figure 6-5 Robotic workspace analysis in a 1200 mm confined ship block. The illustration depicts the working envelope (green) relative to the longitudinal stiffeners and bottom plate, where: (a) a transverse floor plate is hidden to facilitate a clear front-view visibility of the robot's kinematic configuration within a structure featuring two longitudinals between two side girders; and (b) the inner bottom plate is hidden to

provide a top-down visualisation of the manipulator's reach in a more densely reinforced structure with five longitudinals between two side girders.

6.3.5 Simulation Environment and Robot Configuration

The simulation was developed using ABB RobotStudio 2023, utilising its Virtual Controller technology to mirror the real-world behaviour of the robot's IRC5 controller. The IRB 1200 robot, characterised by its compact footprint and high-speed motion, was selected due to its suitability for restricted industrial environments (X. Wang et al., 2020). Three distinct mounting scenarios were modelled within a 1.2-meter height constraint:

1. Floor-Mounted: Robot base fixed to the bottom plate.
2. Elevated on Stiffeners: Robot base positioned atop longitudinal stiffeners to facilitate transversal movement.
3. Inverted (Upside-Down): Robot mounted to the overhead deck structure.

To ensure a controlled comparative analysis, all simulations were executed using identical operational parameters across the three mounting configurations. Specifically, the welding path and seams remained constant, following the standardised U-shaped trajectory within the double-bottom compartment. Furthermore, kinematic performance was evaluated under uniform dynamic constraints, with the welding speed and robot movement speed (TCP velocity) synchronised across all scenarios (Hashemzadeh et al., 2022). This approach eliminates operational variables, ensuring that any observed differences in collision

frequency or reachability are solely attributable to the robot's spatial positioning and mounting strategy (Q. Shi et al., 2026).

6.3.6 Kinematic and Collision Detection Setup

During the simulation process, multiple operational parameters were synchronised and recorded for comprehensive analysis, including Total Motor Energy, Total Motor Power, Linear Acceleration, and TCP Speed. Furthermore, kinematic data comprising individual joint movements J_1 to J_6 (illustrated in Figure 6-6), Cartesian XYZ positions, and Collision Signals were captured to evaluate the manipulator's behaviour within the confined space.

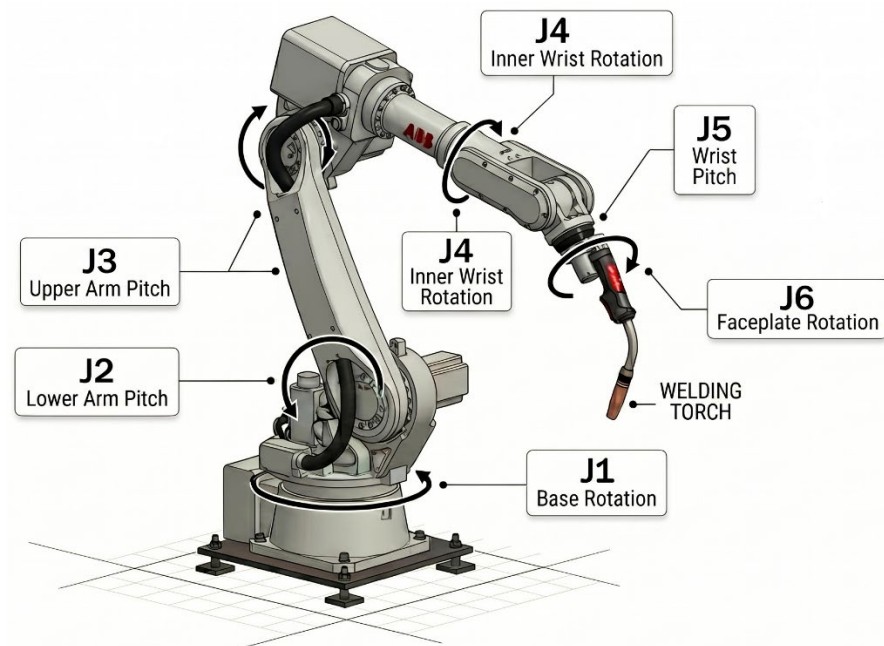


Figure 6-6 Kinematic configuration of the 6-axis welding robot.

Among these metrics, the Total Motor Energy recorded in the simulation excludes the welding arc energy and focuses solely on the mechanical work performed

by the actuators. This is calculated by integrating the product of joint torque (τ) and angular velocity (ω) over the total cycle time, as expressed in Equation (6.1):

$$E_{total} = \int_0^t \sum_{i=1}^n |\tau_i(t) \cdot \omega_i(t)| dt \quad (6.1)$$

where (n) represents the six degrees of freedom of the IRB 1200 manipulator. To ensure high-precision collision analysis, the Collision Detection set was configured to monitor all robot links (Axes 1–6) against the ship's internal geometry. A binary collision signal $C(t)$ is monitored throughout the trajectory, defined in Equation (6.2):

$$C(t) = \begin{cases} 1 & \text{if } dist(R, S) \leq \epsilon \\ 0 & \text{if } dist(R, S) > \epsilon \end{cases} \quad (6.2)$$

where $dist(R, S)$ is the Euclidean distance between the robot geometry and the structural boundaries, and ϵ represents the safety threshold (specified as $\epsilon = 10$ mm). Furthermore, World Zones were defined using RAPID programming to create virtual safety boundaries. These zones automatically monitor the robot's TCP (Tool Centre Point) and elbow position (Axis 3) to detect structural interference during transversal transitions between stiffener bays (Arif et al., 2022).

The automated path planning was subjected to continuous, dynamic collision detection (Wong et al., 2023). This ensures that the robot arm, wrist, and torch assembly do not intersect with any part of the surrounding hull structure (webs, frames, adjacent stiffeners) throughout the entire trajectory (Ahmed et al., 2016). For validated, collision-free paths, the total travel time, welding time, and necessary repositioning time were aggregated to calculate the optimised robotic cycle time. This metric is used to quantify the efficiency gains of the automated process compared to established manual times (Lin & Shaw, 2017).

6.3.7 Design for Automation Modelling and Structural Loading Setup

To validate that the proposed Design for Automation (DfA) profile modifications do not compromise the vessel's structural safety, a localised three-dimensional Finite Element (FE) model was developed using ANSYS Static Structural. The model represents a representative cargo tank double-bottom compartment of the 7,700 DWT product tanker (LOA = 117 m, B = 17.7 m, D = 9.2 m), which is characterised by a double bottom height of 1200 mm.

The geometry models utilise standard marine structural steel with a yield strength (σ_y) of 235 MPa. The density is taken as 7850 kg/m³ with a Young's modulus of 200 GPa and a Poisson's ratio of 0.3. High-quality shell elements were used to mesh the plates, transverse web frames, longitudinal stiffeners, and floors to ensure accurate bending and shear stress representation at structural intersections (Nguyen & Oterkus, 2020).

6.4 Robotic Welding Simulation Results

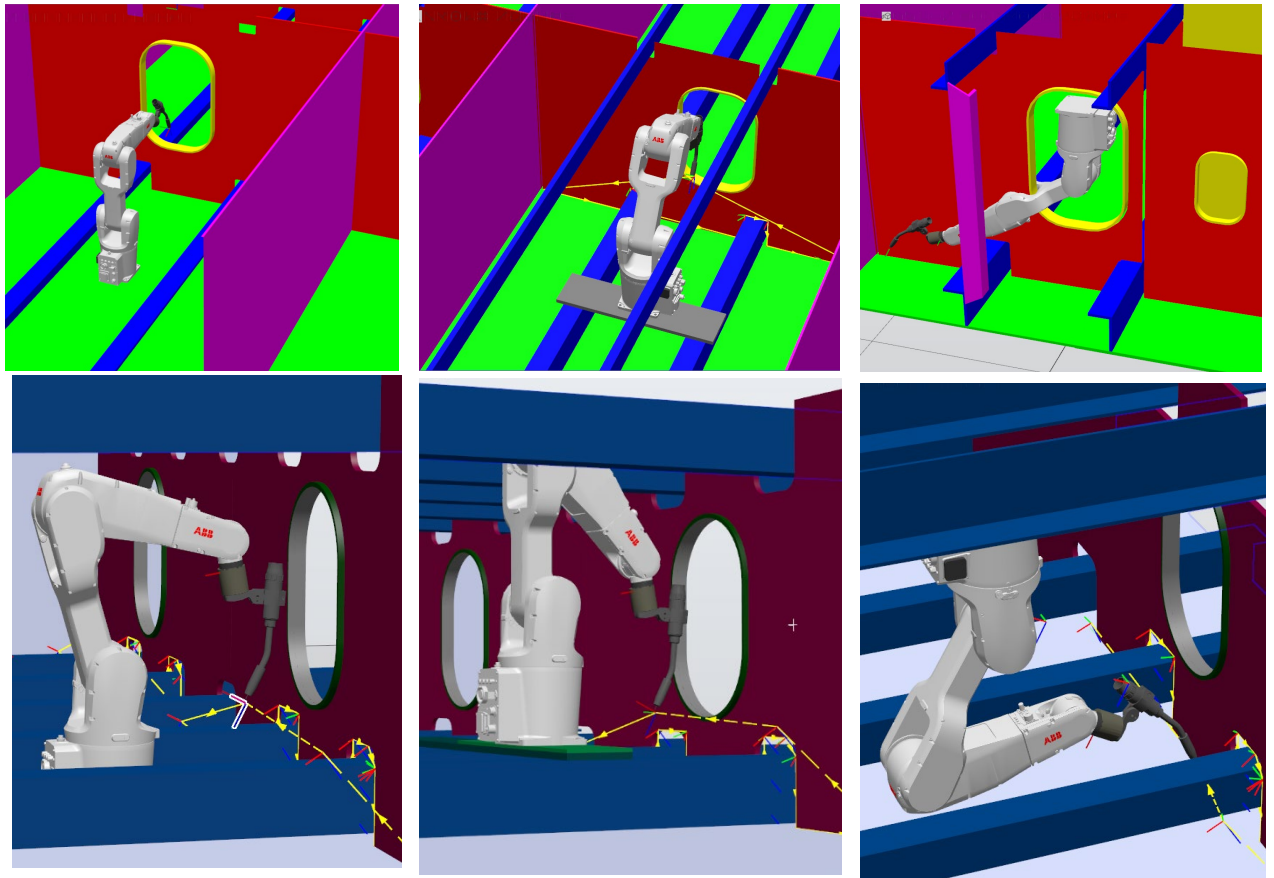
6.4.1 Workspace Envelope and Reachability Analysis

The simulation performed in the Digital Twin Prototype (DTP) environment allowed for a precise mapping of the robot's workspace within the 1.2m confined height constraint (Wong et al., 2023).

- **Floor-Mounted Configuration:** As shown in Figure 6-7(a), the floor-mounted position offers high stability but is significantly limited by the height of the longitudinal stiffeners, which act as physical barriers to the robot's lower arm movements. Under this validated trajectory and elevated mounting configuration, the robotic end-effector demonstrated successful collision-free accessibility along

the designated longitudinal fillet seams within the single test bay evaluated in this study. This kinematic performance is specific to the defined baseline dimensions of the 7,700 DWT double-bottom block (1.2 m vertical height and 600 mm stiffener spacing) and the evaluated torch geometry. It should be noted that applicability to differing structural arrangements, such as narrower bays or sections with complex transverse tripping brackets, would require independent trajectory planning and reachability assessment. However, the robot's reach was limited to its immediate compartment, requiring manual relocation to access adjacent areas. However, the robot's reach was limited to its immediate compartment, requiring manual relocation to access adjacent areas.

- **Elevated Configuration (On-Stiffener):** The elevated position in Figure 6-7(b) demonstrates a strategic advantage in avoiding floor-level obstacles, though it necessitates precise management of the 'elbow' clearance (Axis 3) relative to the inner bottom plate. By positioning the robot base on top of the stiffeners, the tool centre point (TCP) could access the welding paths. However, the effective workspace was compressed vertically, reducing the available "overhead" clearance for the robot's elbow joint (Axis 3).
- **Inverted Configuration:** While providing clear floor space, this configuration struggled with "singularities" and joint limit reaches when attempting to weld the lowest sections of the structure. The inverted configuration in Figure 6-7(c) theoretically maximises floor space, the simulation reveals a higher collision risk with the upper structural boundaries during the U-shaped welding sequence.



(a)

(b)

(c)

Figure 6-7 Comparative configurations of robotic welding units within the double-bottom compartment featuring both two longitudinal stiffeners and five longitudinal stiffeners between side girders: (a) floor-mounted configuration, where the robot base is positioned directly on the bottom shell; (b) elevated configuration, with the robot mounted atop the longitudinal stiffeners to enhance transversal reach; and (c) inverted configuration, illustrating an overhead mounting strategy. Each scenario is evaluated for kinematic reachability and collision avoidance within the 1200 mm vertical constraint.

6.4.2 Collision Detection and Kinematic Interference

Quantitative collision analysis was conducted using the RobotStudio Collision Detection set, monitoring the interaction between the robot links and the ship's CAD geometry.

- **Axis 3 Interference:** In both the Elevated and Inverted configurations, Axis 3 was identified as the primary point of failure. In the elevated position, the robot's elbow frequently made contact with the overhead deck during the "home" position or when transitioning between weld starts. A comparative collision analysis was performed to evaluate the spatial clearance of the robot during the lower sections of the welding trajectory. As illustrated in Figure 6-8, the floor-mounted configuration (b) poses a higher risk of interference between the robot's lower arm links and the longitudinal stiffener's base, especially when navigating tight corners. Conversely, by adopting the elevated mounting strategy (a), the robot's base is shifted vertically, effectively lifting the primary joints above the most congested zone of the compartment. This elevation provides a critical 'safety buffer' that eliminates potential contact with the floor-level structural elements. The simulation confirms that while both positions may reach the target, the elevated configuration offers a more robust kinematic solution by significantly reducing the probability of proximity-related collisions during high-speed movements.

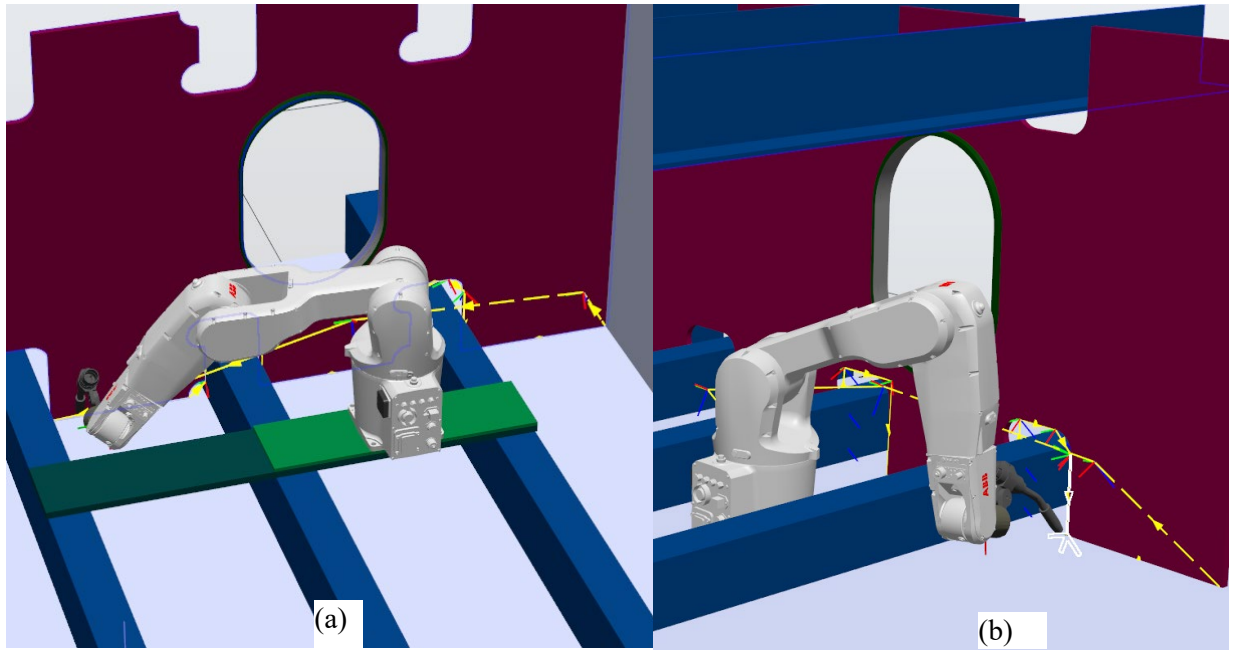


Figure 6-8 Comparative visualisation of collision avoidance strategies: (a) elevated mounting position, showing improved clearance between the robot arm and the structural floor; and (b) floor-mounted (sitting on base plate) configuration, illustrating the restricted gap between the manipulator's lower joints and the longitudinal stiffeners.

- **Link-to-Stiffener Collision:** In the inverted position, a critical collision occurred when the robot attempted to reach downward. The physical volume of Axis 4 and the welding torch assembly collided with the longitudinal stiffener's flange, particularly when the weld path required a steep torch angle. Despite its potential for maximising floor space, the inverted mounting configuration encounters severe kinematic limitations within the 1200 mm vertical clearance of the ship block. As demonstrated in the collision analysis (Figure 6-9), the manipulator's upper arm (Axis 3) consistently interferes with the overhead inner bottom plate

during the execution of the U-shaped welding trajectory. This structural collision occurs because the inverted base position forces the robot's elbow to extend upwards to maintain the necessary torch angle for the fillet weld. These findings suggest that without a significant increase in compartment height or a custom-designed low-profile offset for the robot base, the inverted strategy remains infeasible for standard double-bottom assembly due to these recurring spatial conflicts.

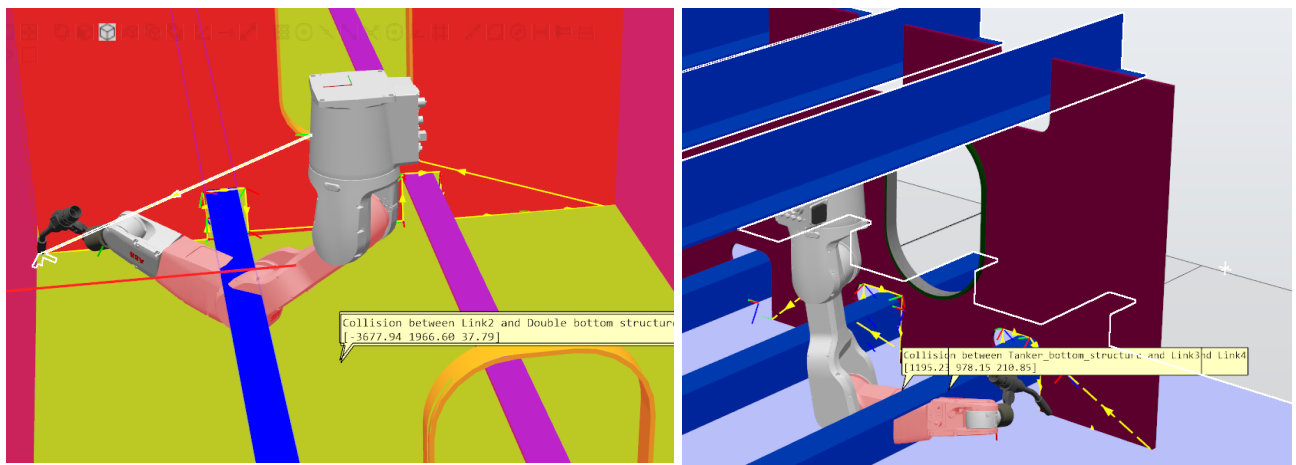


Figure 6-9 Collision detection analysis for the inverted mounting strategy. The simulation highlights a critical contact point (indicated by the red highlighted zone) where the robot's Axis 3 (elbow) interferes with the bottom longitudinal. This spatial conflict occurs during the peak of the U-shaped welding path, confirming the kinematic

incompatibility of the inverted configuration within the restricted 1200 mm overhead boundary.

6.4.3 Simulation Results for Two-Stiffener Operation Between Side Girders

6.4.3.1 Floor-Mounted Configuration (Sitting on Base Plate)

The operational performance of the IRB 1200-5/0.9, positioned on the base plate for a two-stiffener welding sequence, is illustrated in Figure 6-10. The TCP Speed profile confirms the precise execution of the welding cycle, strictly following the programmed velocities of 10 mm/s for down hand welding and 5 mm/s for vertical segments. Rapid transitions between seams and movements to the home position were successfully executed at 100 mm/s and 200 mm/s, respectively. It is important to note that the Total Motor Power and Total Motor Energy metrics solely reflect the energy consumption required for the mechanical movement of the robot arm, excluding the electrical energy used for the welding arc. The Linear Acceleration remained stable during active welding, with controlled impulses occurring only during high-speed repositioning, indicating a highly reliable motion control system.

The sequential simulation captures located beneath the performance charts correspond to critical time steps throughout the process, providing a visual timeline of the operation. These snapshots verify the robot's kinematic reach and structural clearance as it navigates the U-shaped trajectories of both stiffeners. From a safety standpoint, the floor-mounted configuration proves highly effective for this structural geometry; the Collision Signal remains at zero across the entire sequence. Furthermore, the absence of Near Wrist Singularity or Near Joint Limit triggers, as evidenced by the manipulator's steady configuration in the time-step images,

demonstrates that mounting the robot on the base plate provides the most stable kinematic workspace and optimal clearance within the 1200 mm height constraint.

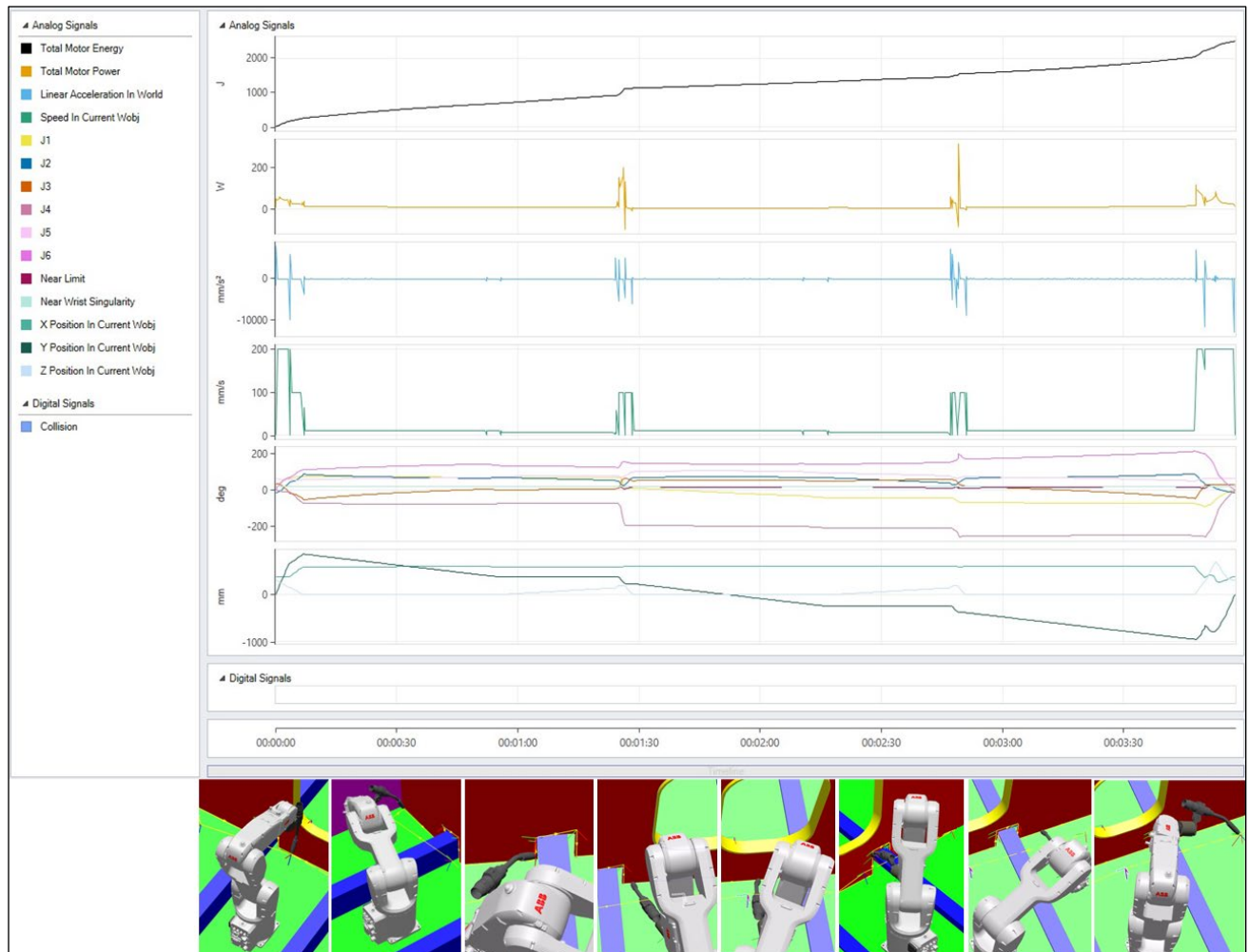


Figure 6-10 Dynamic analysis and time-step visual verification of the floor-mounted robot configuration for a two-stiffener task: (top) Performance charts detailing TCP Speed, Power/Energy (mechanical only), and zero-collision safety monitoring; (bottom) Sequential simulation captures showing the progression of the welding path from the first to the second stiffener.

6.4.3.2 Elevated Configuration (Sitting on Stiffeners)

The operational performance of the IRB 1200-5/0.9, mounted in an elevated position directly atop a stiffener for a two-stiffener welding sequence, is presented in Figure 6-11. The TCP Speed profile confirms the precise execution of the welding cycle, strictly following the programmed velocities of 10 mm/s for down hand welding and 5 mm/s for vertical segments. Rapid transitions between seams and movements back to the home position were successfully executed at 100 mm/s and 200 mm/s, respectively. It is important to note that the Total Motor Power and Total Motor Energy metrics solely reflect the energy consumption required for the mechanical movement of the robot arm, excluding the electrical energy used for the welding arc. The Linear Acceleration remained stable during active welding, with controlled impulses occurring only during high-speed repositioning, indicating a reliable motion control system.

The sequential simulation captures located beneath the performance charts correspond to critical time steps throughout the process, providing a visual timeline of the operation from start to finish. These snapshots verify the robot's kinematic reach and structural clearance as it navigates the U-shaped trajectories of both stiffeners. From a safety standpoint, the elevated configuration proves highly effective during the active phase, as the Collision Signal remains at zero across the entire welding sequence. However, the data and visual sequence identify a small risk of collision during the final stage of the process. As the robot performs the high-speed retraction to the initial home position, the reduced vertical clearance between the elevated base and the overhead side-girder flanges creates a proximity hazard for the robot's upper

arm links. Despite this minor risk during the final transition, as evidenced by the manipulator's steady configuration in the time-step images, the absence of Near Wrist Singularity or Near Joint Limit triggers demonstrates that the elevated mounting provides excellent dexterity for the primary task within the 1200 mm height constraint.

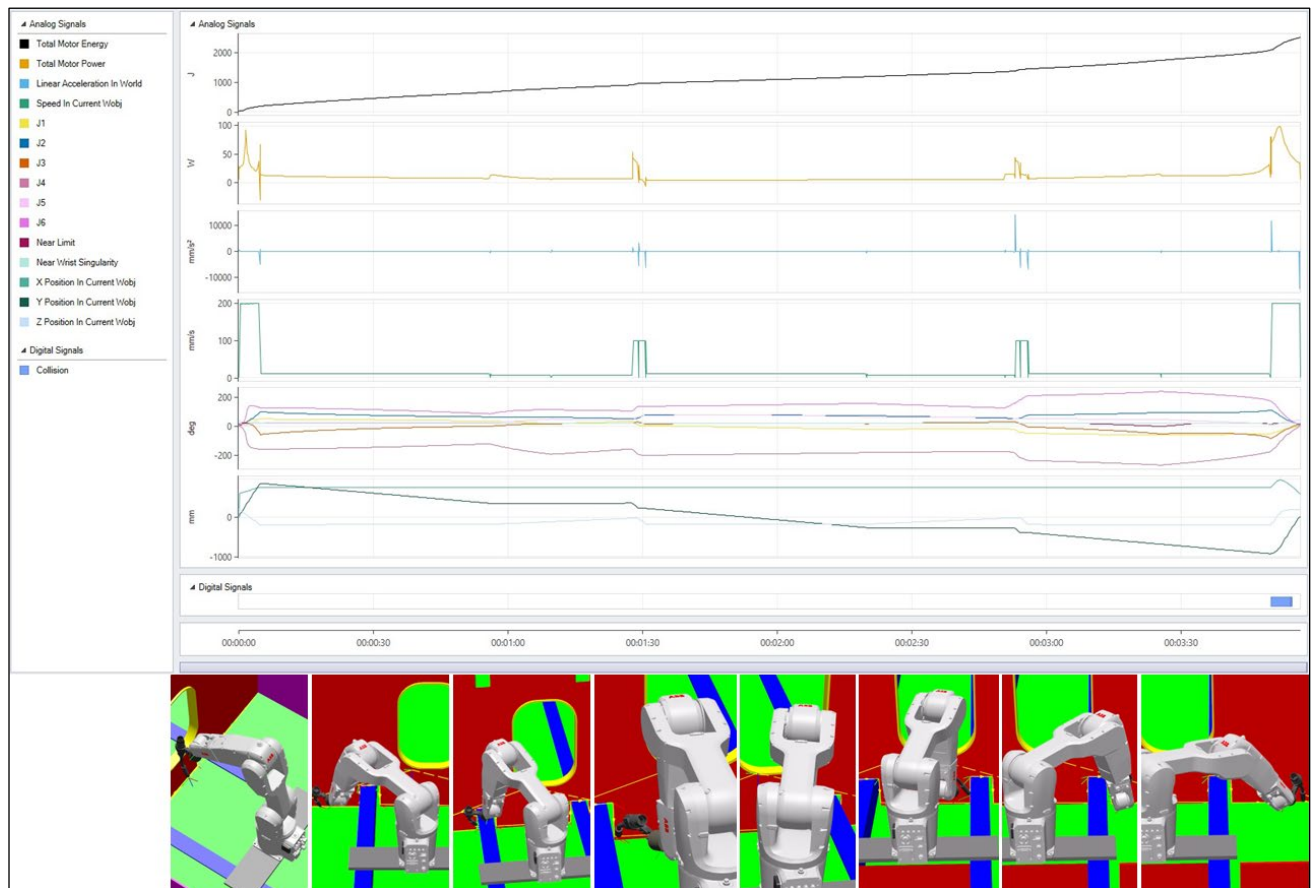


Figure 6-11 Dynamic analysis and time-step visual verification of the elevated robot configuration for a two-stiffener task: (top) Performance charts detailing TCP Speed, Power/Energy (mechanical movement only), and safety monitoring; (bottom) Sequential simulation captures showing the progression of the welding path and identifying proximity risks during the final return-to-home manoeuvre.

6.4.3.3 Inverted Mounting Configuration

The operational performance of the IRB 1200-5/0.9 in an inverted mounting position, suspended from the inner bottom structure, is detailed in Figure 6-12. The TCP Speed profile confirms a precise execution of the welding cycle within a total duration of 235.6 s, adhering to the programmed velocities of 10 mm/s for down hand welding and 5 mm/s for vertical segments. Rapid transitions between seams were performed at 100 mm/s, while the initial and final manoeuvres reached 200 mm/s. The Linear Acceleration remained stable during active welding phases, with controlled impulses occurring during high-speed repositioning.

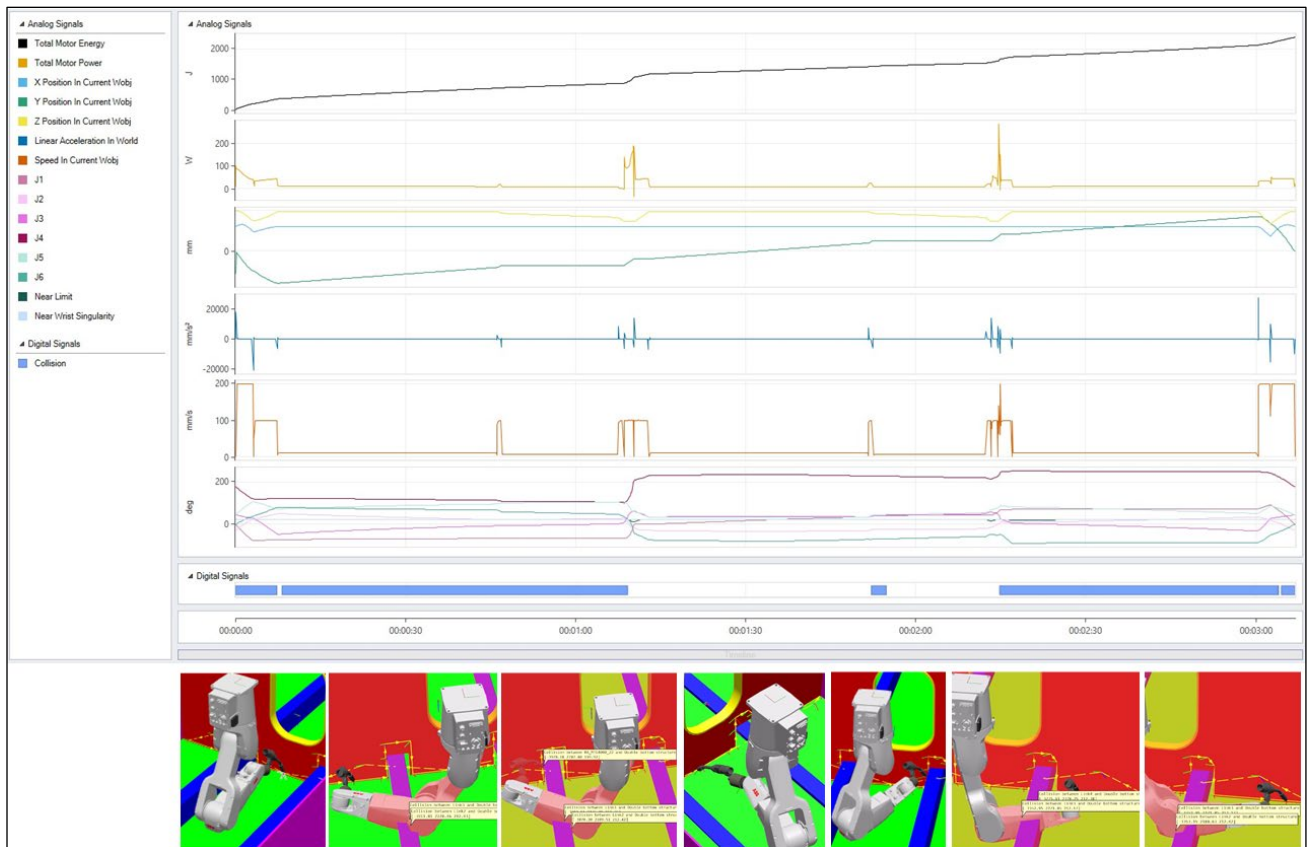


Figure 6-12 Dynamic analysis and visual verification of the inverted robot configuration: (top) Simulation environment showing the suspended IRB 1200-5/0.9;

(bottom) Performance charts illustrating TCP Speed, Total Motor Power/Energy (mechanical only), and a Collision Signal (blue bars) indicating major structural interference throughout the process.

Notably, the Total Motor Power and Total Motor Energy metrics reflect only the energy consumption required for the mechanical movement of the robot arm, excluding the electrical energy utilised for the welding arc. While the motor power peaked at 304.8 W, indicating an efficient power distribution, the safety monitoring results reveal significant spatial constraints. As shown in the blue bar chart (Collision Signal), major collision events occurred throughout the welding process. These interferences indicate that while the inverted orientation optimises reach for certain segments, the limited 1200 mm height of the double-bottom structure causes the robot's upper arm or elbow links to frequently contact the side-girder flanges or the stiffener tops during the U-shaped trajectory. Despite the absence of Near Wrist Singularity or Near Limit triggers, these persistent collisions demonstrate that without a specialised offset bracket or a more restricted path planning strategy, the standard inverted mounting is physically unfeasible for this specific ship-block geometry.

6.4.4 Simulation Results for Five-Stiffener Operation Between Side Girders

6.4.4.1 Floor-Mounted Configuration (Sitting on Base Plate)

The operational performance of the IRB 1200-5/0.9 in a floor-mounted position, positioned centrally to process five stiffeners within the double-bottom structure, is summarised in Figure 6-13. The TCP Speed profile confirms a high-precision execution of the extended welding cycle, adhering to the programmed velocities of 10 mm/s for down hand welding and 5 mm/s for vertical segments, with rapid transitions

between seams and to the home position performed at 100 mm/s and 200 mm/s, respectively. The Linear Acceleration remains stable throughout these phases, exhibiting controlled impulses only during high-speed repositioning manoeuvres, which indicates a robust motion control system even when operating at the robot's maximum reach envelope.

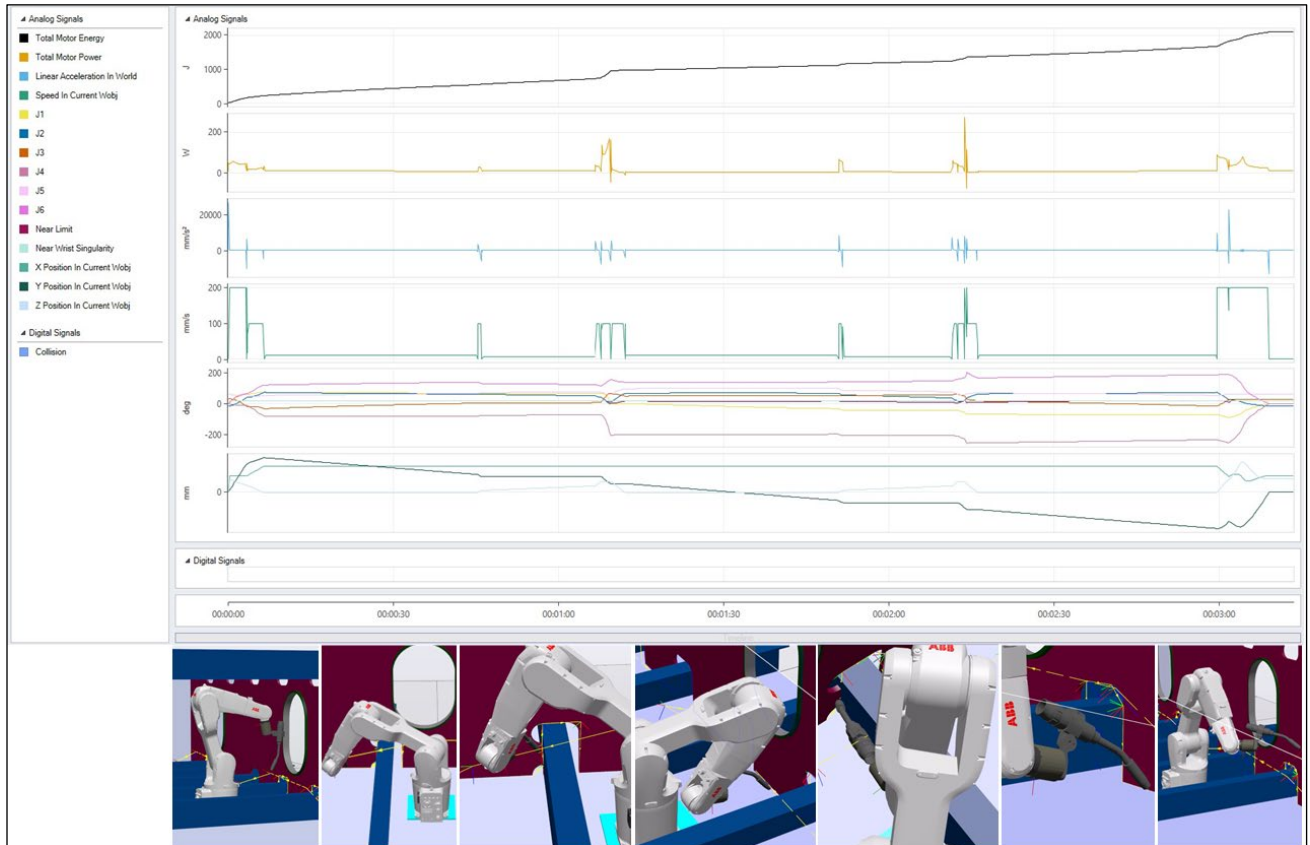


Figure 6-13 Dynamic analysis and visual verification of the floor-mounted robot configuration for five stiffeners: (top) 3D simulation environment illustrating the reach of the IRB 1200-5/0.9; (bottom) Performance charts detailing TCP Speed (5–10 mm/s welding and 100–200 mm/s rapid moves), Total Motor Power/Energy (mechanical only), and zero-collision safety monitoring.

Notably, the Total Motor Power and Total Motor Energy metrics represent only the energy consumption required for the mechanical movement of the robot arm and do not include the electrical energy utilised for the welding arc. The motor power peaks at 314.6 W during high-speed transitions, while the Total Motor Energy follows a consistent linear accumulation over the duration of the multi-stiffener task. From a safety and feasibility perspective, the floor-mounted configuration proves highly effective for this large-scale task; the Collision Signal remains at zero throughout the entire five-stiffener sequence, including all vertical and horizontal welding paths. Furthermore, despite the increased reach required to access the outer stiffeners, the absence of Near Wrist Singularity or Near Joint Limit triggers demonstrates that the floor-mounted setup provides the most stable kinematic workspace and optimal structural clearance for processing multiple stiffeners from a single base position.

6.4.4.2 Elevated Configuration (Sitting on Stiffeners)

The operational performance of the IRB 1200-5/0.9 in an elevated position, i.e. mounted directly atop a central stiffener, to process a sequence of five stiffeners is summarised in Figure 6-14. The TCP Speed profile confirms a high-precision execution of the extended welding cycle, maintaining programmed velocities of 10 mm/s for down hand welding and 5 mm/s for vertical segments, with rapid repositioning and return-to-home manoeuvres performed at 100 mm/s and 200 mm/s, respectively. The Linear Acceleration remains stable throughout these phases, indicating a robust motion control system. Notably, the recorded Total Motor Power (peaking at 353.4 W) and Total Motor Energy represent only the energy consumption

required for the mechanical movement of the robot arm and do not include the electrical energy utilised for the welding arc.

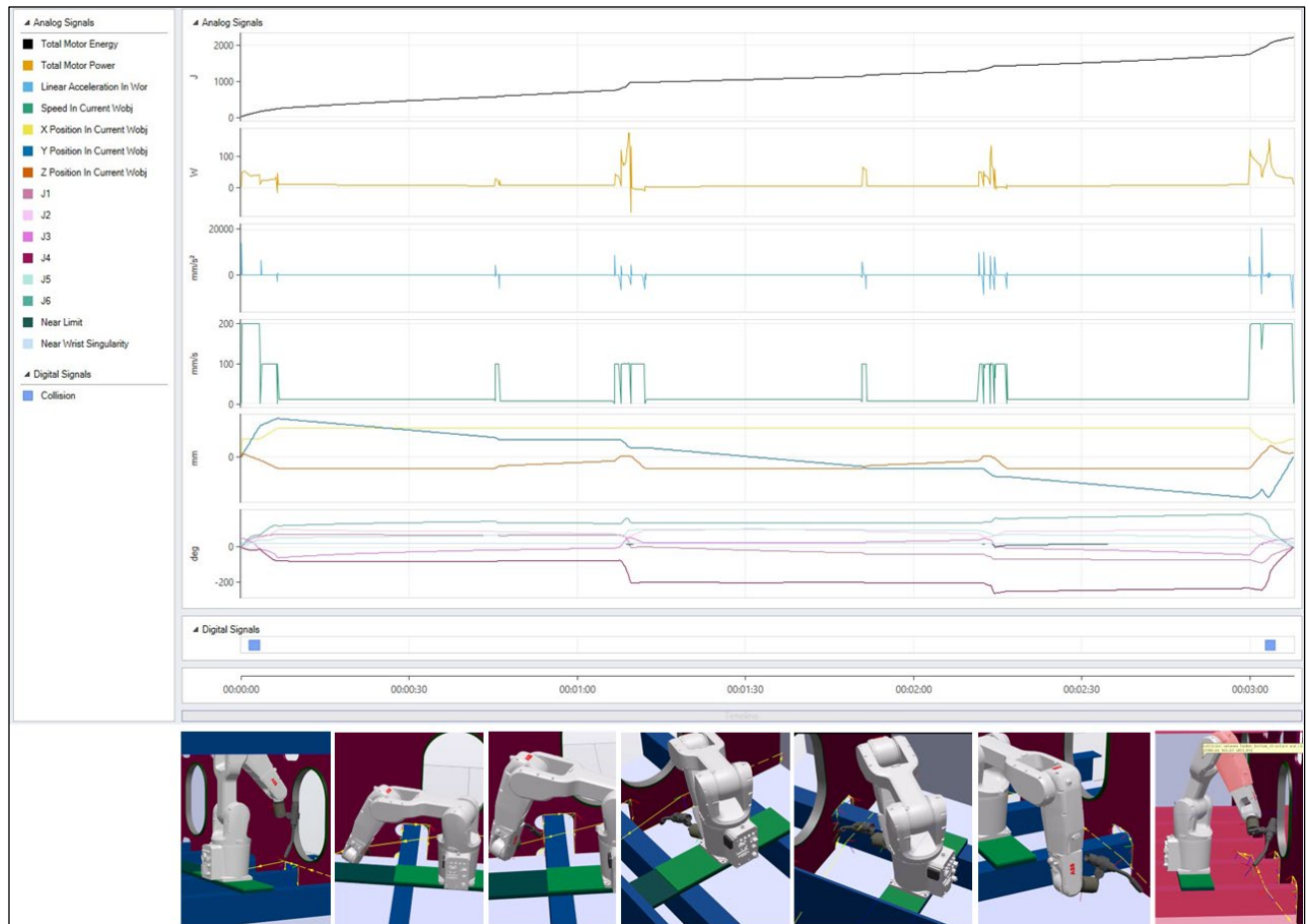


Figure 6-14 Dynamic analysis and time-step visual verification of the elevated robot configuration for a five-stiffener task: (top) Performance charts detailing TCP Speed, Total Motor Power/Energy (mechanical only), and safety monitoring; (bottom) Sequential simulation captures showing a collision-free welding process and identifying proximity risks during high-speed initial/final manoeuvres.

The series of simulation captures provided below the performance charts correspond to critical time steps in the 233.5-second cycle, offering visual verification of the robot's kinematic reach and structural clearance. From a safety perspective, the

visual sequence confirms that the welding process itself is entirely collision-free, as the elevated mounting provides optimal torch orientation for all five stiffeners. However, the data reveals a small risk of collision during the rapid non-productive phases, specifically during the initial approach from the home position and the final retraction. This localised risk occurs because the elevated base reduces the vertical buffer between the robot's "elbow" (Link 3) and the overhead side-girder flanges. Despite this minor proximity risk during high-speed transitions, the absence of Near Wrist Singularity and Near Joint Limit triggers throughout these visual stages proves that the elevated configuration remains a viable strategy for multi-stiffener operations within the 1200 mm height constraint.

6.4.4.3 Inverted Mounting Configuration

The operational performance of the IRB 1200-5/0.9 in an inverted mounting position, suspended from the upper deck to process a sequence of five stiffeners, is summarised in Figure 6-15. The TCP Speed profile confirms the execution of the welding cycle adhering to programmed velocities of 10 mm/s for down hand welding and 5 mm/s for vertical segments, with rapid transitions between seams and home manoeuvres performed at 100 mm/s and 200 mm/s, respectively. Crucially, the recorded Total Motor Power (peaking at 304.8 W) and Total Motor Energy represent only the energy consumption required for the mechanical movement of the robot arm and do not include the electrical energy utilised for the welding arc. While the Linear Acceleration remained stable during the active welding phases, the safety monitoring data reveals severe spatial limitations.

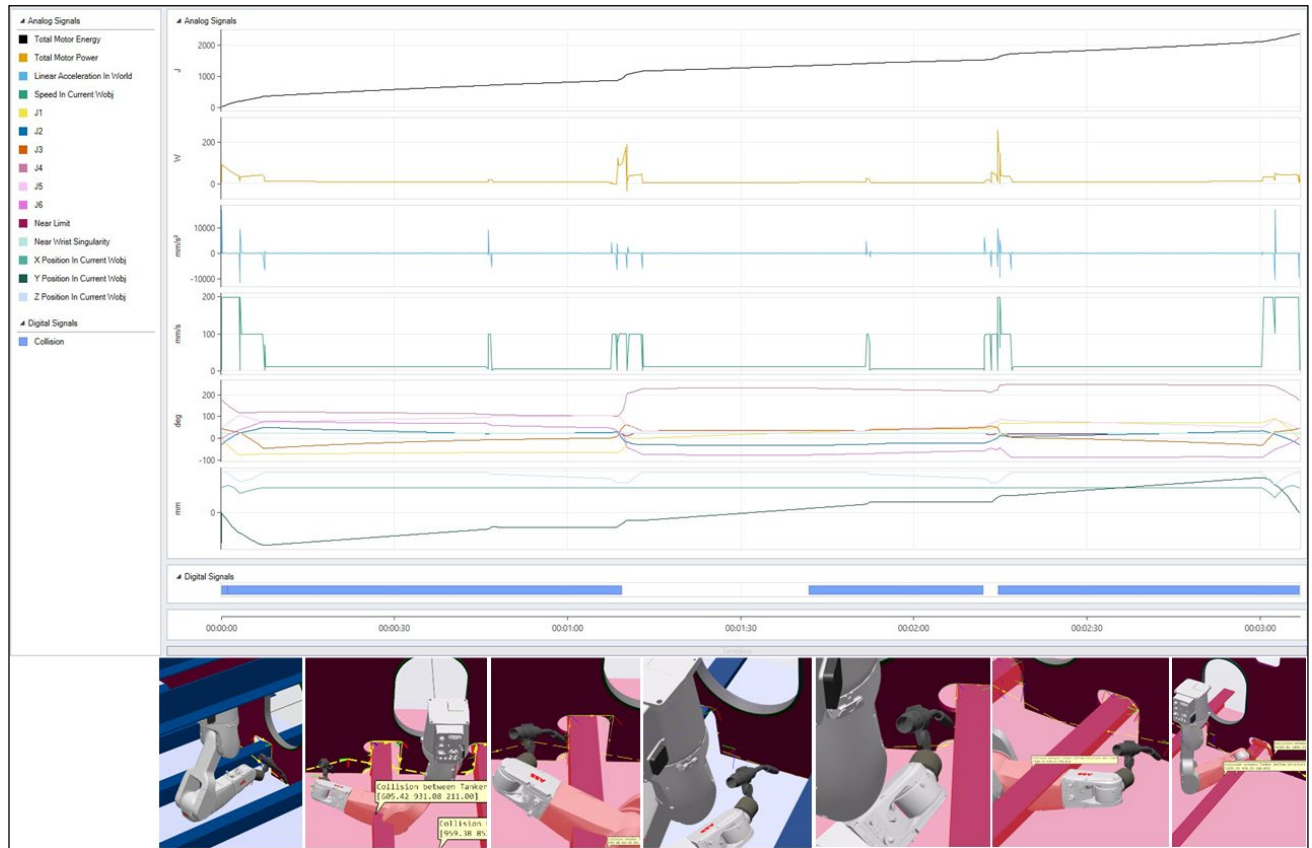


Figure 6-15 Dynamic analysis and time-step visual verification of the inverted robot configuration for a five-stiffener task: (top) Performance charts detailing TCP Speed, Power/Energy (mechanical only), and a Collision Signal (blue bars); (bottom) Sequential simulation captures where red highlights indicate structural interference occurring throughout the welding process.

The sequential simulation captures provided below the performance charts correspond to critical time steps in the process, providing a visual timeline of the operation. As clearly indicated by the red warning highlights in the 3D captures and the corresponding blue bar chart (Collision Signal), major collision events occurred persistently during the actual welding process. These interferences demonstrate that the inverted orientation, while optimising reach for certain angles, causes the robot's

primary links to frequently strike the longitudinal stiffeners and the side-girder flanges due to the restricted 1200 mm height of the double-bottom compartment. Despite the absence of Near Wrist Singularity or Near Joint Limit triggers, the high frequency of these collision signals confirms that the standard inverted mounting is physically unfeasible for processing multiple stiffeners in this specific structural geometry without a significant redesign of the mounting bracket or a more constrained path-planning algorithm.

6.4.5 Comparative Analysis of Robotic Mounting Configurations

The performance of the robotic welding system was evaluated across three distinct mounting configurations based on six critical operational criteria. The comparative data, as summarised in Table 6-1, highlights the fundamental trade-offs between accessibility, kinematic safety, and operational efficiency within the 1.2m confined space.

Table 6-1 Comparative analysis of the three robot mounting configurations.

Analysis Criteria	Robot on Bottom Plate (Floor)	Robot on Stiffener (Elevated)	Robot Positioned Upside Down
Welding Reachability	Excellent for fillet joints between the floor and bulkheads/stiffeners.	Limited to upper areas; difficult to reach lower corner fillets due to self-obstruction.	Difficult to navigate the torch into narrow path without the arm hitting the stiffeners.
Collision Risk	Minimum: More clearance for the elbow, though welding cables risk snagging on stiffeners.	Medium: The robot's elbow (Axis 3) is at significant risk of hitting the ceiling due to the high base elevation.	High: Frequent collisions between the robot arm/torch and stiffener edges when reaching downward.
Motion Stability	Most stable as it is supported directly by flat plate.	Risk of vibration if the mounting bracket on the stiffener is not sufficiently rigid.	Requires a heavy-duty support structure (gantry or rail) attached to the ceiling.

Analysis Criteria	Robot on Bottom Plate (Floor)	Robot on Stiffener (Elevated)	Robot Positioned Upside Down
Degrees of Freedom (DOF)	Flexible: Standard kinematics allow for smooth movement along the entire longitudinal path.	Limited: Robot often reaches "Joint Limits" trying to tilt the torch in a compressed height.	Complex: Inverted kinematics increase the risk of "Singularity" and structural interference.
Movement Mechanism	Robot must be detached and remounted manually for every stiffener bay.	Robot slides on a rail system bridging two stiffeners.	Robot slides on a heavy-duty rail system.
Cycle Time Efficiency	Inefficient: High downtime due to repetitive setup and calibration.	Highly Efficient: Continuous movement without stopping the system using a simple rail mechanism.	Efficient: Continuous movement using a heavy-duty support structure

6.4.5.1 Welding Reachability and Kinematic Constraints

The floor-mounted configuration demonstrated superior performance for lower fillet joints, providing an unobstructed path between the floor and bulkheads. In contrast, the upside-down (inverted) position faced severe navigation challenges, as the manipulator's arm frequently interfered with stiffener edges when attempting to reach downward paths. The elevated configuration atop stiffeners, while offering mobility, was found to be limited to upper structural areas, struggling to reach lower corner fillets due to self-obstruction caused by its base height.

6.4.5.2 Collision Risk and Axis Interference

A critical finding in the collision analysis is the vulnerability of Axis 3 (the elbow joint) in the elevated position. Due to the high base elevation, the robot's elbow is at a significant risk of striking the ceiling structure. The inverted position, however, presented the highest overall collision risk between the robot arm/torch and stiffener flanges. The floor-mounted setup offered the most clearance for robotic links, although it introduced a secondary risk of welding cables snagging on structural protrusions.

6.4.5.3 Degrees of Freedom (DOF) and Motion Stability

The study identified that inverted kinematics significantly increase the complexity of motion planning, raising the likelihood of "Singularity" and structural interference (Ahmed et al., 2016). While the floor-mounted position allows for standard, flexible kinematics and maximum stability, the elevated position often forced the robot to reach its "Joint Limits". This occurred as the system attempted to tilt the welding torch within the compressed vertical space, leading to restricted operational envelopes.

6.4.5.4 Movement Mechanism and Cycle Time Efficiency

The most significant differentiator for industrial application is Cycle Time Efficiency.

- Floor-Mounted: Despite its stability, this setup is highly inefficient for large-scale production, as the robot must be manually detached and remounted for every stiffener bay, leading to repetitive downtime for setup and calibration.
- Inverted: Offers efficiency through continuous movement via heavy-duty rail systems but requires a massive overhead support structure (gantry) which may be impractical for internal ship blocks.
- Elevated: Identified as the most highly efficient model for transversal mobility. By sliding on a simplified rail system bridging two stiffeners, the robot can maintain continuous operation across bays, provided that structural adjustments are made to mitigate the previously identified collision risks.

6.4.6 Comparative Performance Metrics

The performance of each configuration was benchmarked against three key indicators: Reachability, Mobility, and Collision-Free Path Execution.

Table 6-2 Qualitative and quantitative comparison of mounting configurations for robotic welding in a double-bottom structure (1200 mm height)

Configuration	Reachability & Dexterity	Transversal Mobility	Collision Risk	Overall Viability
Floor-Mounted (Base Plate)	Full reachment across all targeted stiffener zones.	Low (Stationary base setup)	Low (Consistent structural clearance)	High (Most stable and safe)
Elevated (Sitting on Stiffener)	Full reachment but requires adjustment for arm configuration to avoid overheads.	High (Ideal for rail/gantry integration)	Moderate (Risk during home-position transition)	Moderate (Preferred for long-span mobility)
Inverted (Suspended)	Very limited reachment due to vertical height constraints.	Moderate (Limited by ceiling rail clearance)	High (Frequent interference during welding)	Low (Not recommended for this geometry)

Based on these results (illustrated in Table 6-2), the Elevated Configuration on stiffeners demonstrated the best balance for future automated shipbuilding, despite the currently detected structural interferences (Baihaqi et al., 2024). This setup allows the robot to act as a mobile unit traversing the stiffener "rails," which is essential for large-scale double-bottom production.

The qualitative assessment in Table 6-3 summarises the strategic decision-making process for robotic integration in confined ship blocks. The Bottom Plate (Floor) mounting is technically the most stable ("Optimal Performance") because it maximises the distance between the robot base and the overhead deck, granting the

best access to fillet joints. However, its "Mobility Issues" pose a significant hurdle for high-volume production where the robot must be moved frequently. The Elevated (On Stiffeners) mounting emerges as the "Most Preferable" solution. While it introduces a "Medium risk" of the robot's elbow (Axis 3) striking the ceiling, this can be mitigated through "structural optimisation" of the path planning. Its primary strength lies in facilitating easy transversal movement, allowing the robot to transition across multiple stiffener bays without the need for complex and heavy gantry systems that are often impossible to fit within a double-bottom compartment. The Inverted mounting is disqualified due to the "High Collision Risk" observed during downward reach, where the compact 1200 mm height forces the manipulator into an awkward kinematic state.

Table 6-3 Comparative Analysis: Advantages and Disadvantages of Robot Mounting Positions

Mounting Position	Recommendation	Key Advantages	Critical Disadvantages
Bottom Plate (Floor)	Optimal Performance	Provides the best vertical clearance and access to floor-level fillet joints.	Mobility Issues: Difficult and labour-intensive to relocate between stiffener bays manually.
On Stiffeners (Elevated)	Most Preferable	Easiest for transversal movement; avoids heavy-duty gantry installation in confined spaces.	Space Constraints: Medium risk of "Axis 3" (elbow) striking the ceiling; requires structural optimisation.
Upside Down (Inverted)	Not Recommended	Clears the floor area; theoretically avoids ceiling collisions for the elbow.	High Collision Risk: Robot arm and torch frequently strike stiffener edges when reaching downward.

6.5 Design for Automation (DfA) Framework for Robotic Welding in Confined Ship Structures

The comparative kinematic simulations of the floor-mounted, inverted, and elevated configurations highlight that satisfying structural weight and strength

requirements alone is no longer sufficient; instead, the physical layout of ship compartments must be actively co-designed with robotic kinematic limits (Pini et al., 2025).

The digital twin analysis demonstrates that the Elevated (On-Stiffener) mounting configuration is the most viable and preferred configuration for industrial-scale deployment. While the floor-mounted position offers excellent localised joint reachability and motion stability, it renders the manipulator a static welding cell, requiring highly repetitive, labour-intensive manual base relocations that severely degrade shipyard cycle-time efficiency (Lin & Shaw, 2017). On the other hand, the inverted configuration is physically hindered by severe, recurring collisions between Axis 4, the welding torch assembly, and the longitudinal stiffener flanges during downward vertical-to-horizontal fillet welding passes.

By positioning the robot base atop the longitudinal stiffeners, the system can utilise the stiffeners as a sliding rail assembly to traverse multiple compartment bays autonomously, drastically reducing production downtime and manual setup interventions (Okumus et al., 2023). Consequently, the Elevated Configuration serves as the baseline and foundation of the proposed Design for Automation (DfA) framework.

However, because raising the robot's base compresses the overhead space and places the manipulator's elbow joint (Axis 3) at a moderate collision risk with the ceiling during high-speed retractions, the structural dimensions must be geometrically coordinated. To transition this baseline into a robust, collision-free shipyard reality,

the following sections establish concrete structural design guidelines, geometric limits, and real-time supervisor protocols derived from these kinematic clearance constraints.

The following framework synthesises the objective of aligning structural dimensions with the robot's physical envelope, ensuring that automated systems can operate with the dexterity required for complex U-shaped welding trajectories without the Non-Productive Time (NPT) associated with constant repositioning.

6.6.1 Mathematical Definition of Vertical Clearance Limit (Rule 1)

Vertical clearance is the primary constraint governing robotic mobility within the 1200 mm height limit of double-bottom structures. The primary point of failure in these environments is the collision of "Axis 3" (the elbow joint) with the overhead inner bottom plate or its associated stiffeners (Efe, 2019).

To prevent structural interference, the vertical clearance must be defined by the relationship between the total compartment height and the physical height of the internal scantlings:

$$\text{Robot Clearance} = H_{\text{double_bottom}} - (h_{\text{web_bottom}} + h_{\text{web_inner_bottom}}) \quad (6.3)$$

where $H_{\text{double_bottom}}$ is the total height (1200 mm), $h_{\text{web_bottom}}$ is the height of the floor stiffener supporting the robot base, and $h_{\text{web_inner_bottom}}$ is the height of the overhead stiffening members.

For the IRB 1200-5/0.9, the following thresholds are derived from kinematic simulations as illustrated in Figure 6-16:

- 935.40 mm: The absolute minimum physical clearance. This figure represents the static distance from the robot's mounting base to the top of the Axis 3 elbow in its

zero-position. Any clearance below this value renders vertical movement physically impossible.

- 940 mm: The relaxed operational margin, accounting for base mounting plates.
- 950 mm: The safer recommended margin for dynamic motion. This buffer is critical to allow the robot to maintain necessary torch-to-joint angles without the elbow striking the ceiling during "air moves" between weld segments.

Adhering to these millimetre-level tolerances allows the robot to maintain a safe home position when elevated on stiffener which is the preferred configuration for transversal mobility. Without this 950 mm buffer, the robot is forced into singular configurations to avoid the ceiling, significantly reducing the "quality" of the manipulability index and increasing the risk of joint-stall errors.

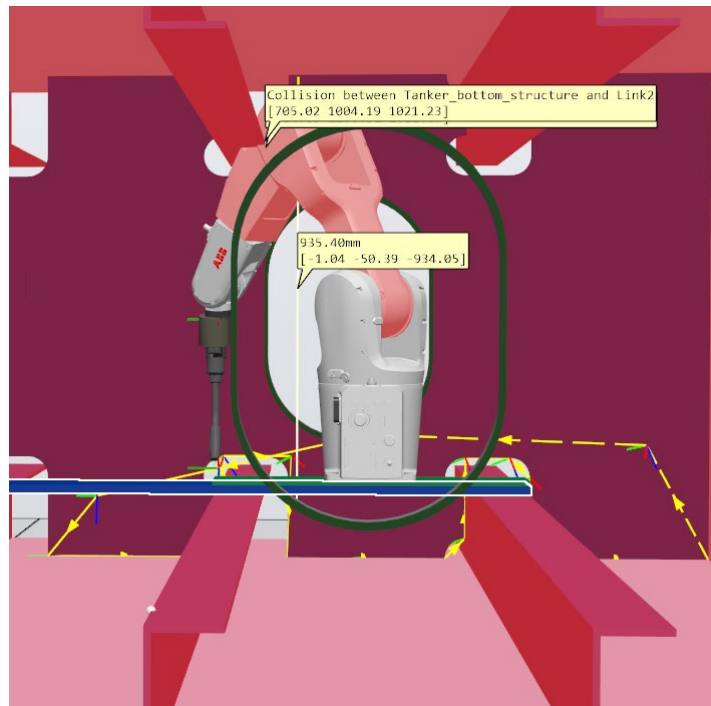


Figure 6-16 Analysis of collision detection and robotic accessibility in the double bottom confined space of the elevated robot configuration.

6.6.2 Boundary Constraints for Flange Widths (Rule 2)

Rule 2 addresses the interaction between the welding torch's physical envelope and the stiffener geometry during the execution of down-hand fillet welding (Hashemzadeh et al., 2022). To ensure torch accessibility and prevent link-to-stiffener collisions, structural designers must enforce the following limit:

$$w_f \leq h_{web_bottom} \quad (6.4)$$

(Flange width must not exceed the web height of the bottom stiffener).

This rule is necessitated by the horizontal volume occupied by Axis 4 (the wrist) and the welding gun assembly. During the "cornering" phase of a U-shaped welding trajectory, the robot must swing the wrist laterally to maintain the optimal torch angle. If the flange width (w_f) exceeds the web height (h_{web}), the wrist volume overlaps with the stiffener's vertical plane. This results in a "Link-to-Stiffener Collision" as identified in the virtual collision heat-maps of Section 4.2 in the source context. Maintaining this ratio ensures the torch has sufficient clearance to reach deep fillet corners without the manipulator's wrist links striking the stiffener edge.

While manual design often favours wider flanges for increased structural stiffness, DfA requires a trade-off. Limiting flange width to these proportions ensures accessibility, preventing the need for complex, low-profile custom torches that increase maintenance costs and reduce arc stability (Lin & Shaw, 2017).

6.6.3 Stiffener Spacing and Robot Reach Coordination (Rule 3)

The final rule focuses on "Transversal Span Efficiency," coordinating structural spacing with the robot's horizontal workspace to minimise logistical downtime.

To optimise bay-to-bay transitions, the structural layout must align with the robot's reach:

- 600 mm: Standard stiffener spacing.
- 1800 mm: Total transversal span covered (3 bays).
- 900 mm: The required horizontal robot reach (IRB 1200-5/0.9).

A robot with a 900 mm reach, when positioned centrally, creates an 1800 mm working diameter. In a structure with 600 mm spacing, this allows the robot to process three full bays from a single mounting position. Furthermore, a 900 mm reach ensures the manipulator has the kinematic dexterity to manoeuvre through standard transversal manhole constraints without the need for disassembly, a requirement identified as critical for minimising NPT.

A robot with a 700 mm reach (IRB 1200-7/0.7) fails to meet the 3-bay requirement, as it cannot reach the outer corners of the adjacent longitudinals, as illustrated in Figure 6-4. This necessitates a multi-fold increase in setup time, as the base must be relocated for every bay. By adopting the 900 mm reach standard, shipyards eliminate the primary driver of non-productive time in confined-space welding.

These rules collectively form the "Robot-Ready" standard for maritime engineering, as summarised in Table 6-4.

Table 6-4 Summary of DfA Limits comparing manual design with robot-ready DfA

Design Parameter	Standard Manual Design	Robot-Ready Design Limit	Primary Kinematic Justification
Vertical Clearance (Axis 3)	Ergonomic focus (>1200mm)	Min. 950mm (Base to overhead)	Prevents Elbow/Ceiling collisions during air-moves.
Flange-to-Web Ratio (Torch)	Stiffness focus while minimising web height ($wf > h_{web}$)	Stiffener thickness variable while keep the flange limit. $wf \leq h_{web_bottom}$	Prevents physical welding torch and wrist collisions during downward weld passes.
Stiffener Spacing (Reach)	Variable load-based spacing	600mm spacing / 1800mm span	Enables 3-bay coverage; minimises repositioning NPT.

6.6.4 Structural Integrity and Strength Validation of the DfA Design

To validate the practical feasibility of the proposed DfA-compliant profile substitution, a localised three-dimensional Finite Element (FE) model representing a critical cargo tank double-bottom compartment of the 7,700 DWT product tanker was developed in ANSYS.

6.6.4.1 Finite Element Modelling and Loading Conditions

To ensure a highly conservative structural safety assessment, the FE model was subjected to a combination of extreme global and localised service loads representing a critical operating state of the vessel (as illustrated in Figure 6-17):

- Global Longitudinal Bending (Hogging Condition): A severe remote bending moment of $2.9619 \times 10^{11} \text{ N} \cdot \text{mm}$ was applied to the model's neutral axis to induce global deck tension and bottom shell compression.
- External Hydrostatic Draft Pressure: An external hydrostatic pressure was applied at the baseline plate, with graduated variable hydrostatic load steps

(represented by steps E, F, G, and H in Figure 18) acting along the curved bilge and side shell plating to simulate the sea draft.

- Self-Weight (Gravity): Standard gravitational acceleration of was applied globally to account for the structural self-weight of the steel plates.
- Internal Cargo Pressure: Static fluid head was applied to the inner bottom plate to simulate cargo load.

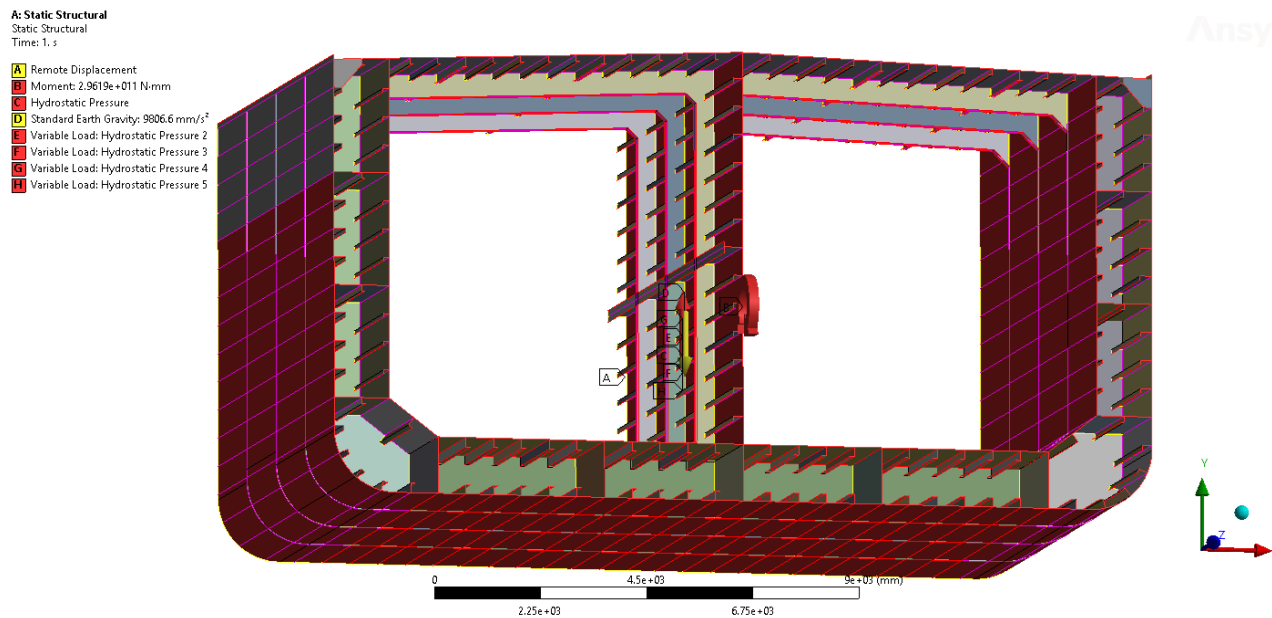


Figure 6-17 Finite element model and boundary conditions of the 7,700 DWT product tanker double-bottom compartment, illustrating applied design loads.

6.6.4.2 Equivalent von-Mises Stress Analysis

The stress contours under these severe loading conditions were compared side-by-side to evaluate local plate-stiffener bending and shear stresses (Figure 6-18):

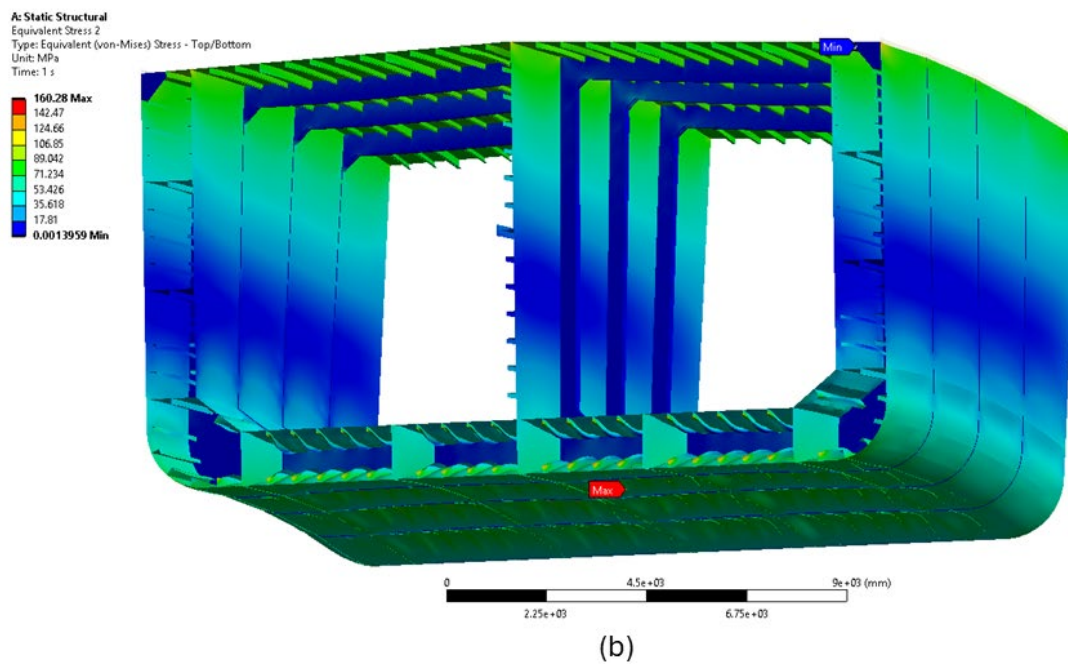
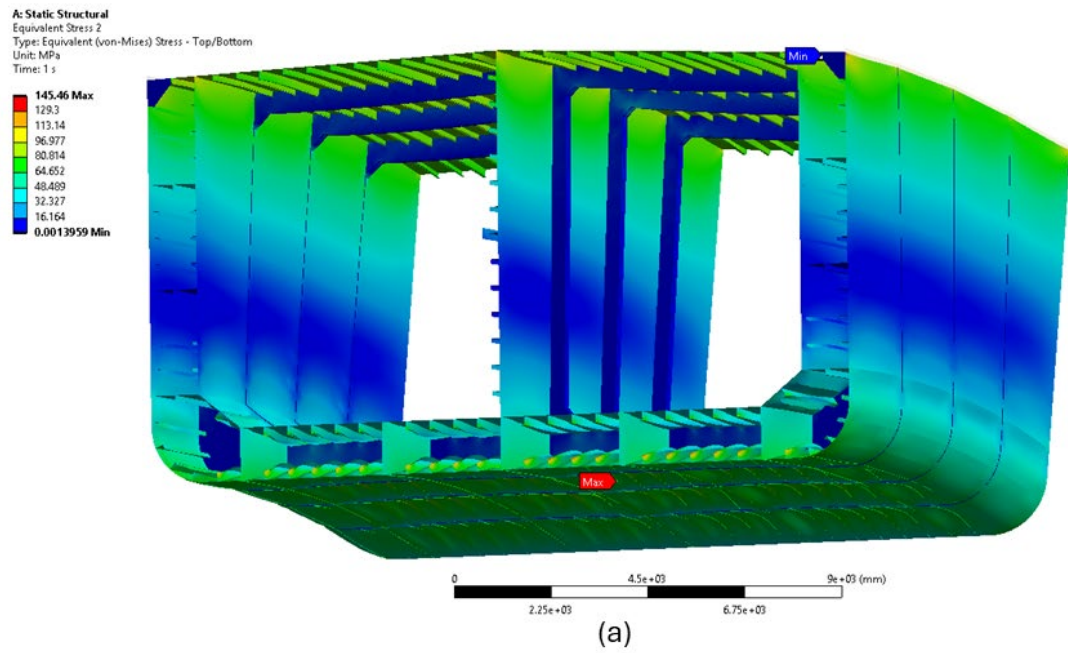


Figure 6-18 Comparison of equivalent (von-Mises) stress distribution under extreme hogging and hydrostatic loading conditions: (a) initial baseline design, and (b) DfA-compliant design.

- Initial Baseline Design (T 200 × 100 × 10 mm profiles): The peak equivalent von-Mises stress is 145.46 MPa, concentrated primarily at the bottom shell plating near the intersection of the floor plate and the central longitudinal girder.
- DfA-Compliant Design (T 150 × 90 × 12 mm) bottom / T 100 × 75 × 12 mm inner bottom): Under the exact same load combination, the peak equivalent stress is 160.28 MPa, localised in a structurally identical pattern.

In term of academic analysis, reducing the bottom longitudinal web height by 25% (from 200 mm to 150 mm) and the overhead longitudinal web height by 50% (from 200 mm to 100 mm) to clear the robot's physical envelope naturally diminishes the localised cross-sectional moment of inertia. This leads to a slight increase of 14.82 MPa (or 10.19) in peak stress. Crucially, the resulting peak equivalent von Mises stress remains well within safe operational limits. For standard marine mild steel (Grade A, nominal yield strength $\sigma_y = 235$ MPa), classification society standards (such as Lloyd's Register and IACS Common Structural Rules) prescribe a permissible design stress limit of $\sigma_{allow} = 175$ MPa, which corresponds to an operational safety utilisation factor of approximately $0.745 \cdot \sigma_y$ (74.5% of material yield strength). Within the multi-objective optimisation framework, this 175 MPa threshold is enforced as a strict **inequality constraint** ($\sigma_{max} \leq \sigma_{allow}$). The observed peak stress demonstrates full regulatory compliance, remaining approximately 31.8% below the nominal material yield strength and securely beneath the mandatory 175 MPa classification threshold, thereby ensuring robust structural resilience against plastic deformation under maximum design lateral loads.

6.6.4.3 Total Deformation Analysis

The global structural stiffness and deflection characteristics were compared to verify that the lower-profile DfA design does not suffer from excessive structural flexibility (Figure 6-19):

- Initial Baseline Design: The maximum total deformation is 7.3121 mm, located at the unsupported mid-span panels of the upper deck and inner bottom plating.
- DfA-Compliant Design: The maximum total deformation is 7.3605 mm, occurring in an identical spatial distribution.

In term of academic analysis, the structural rigidity of the double-bottom assembly is remarkably well-preserved. Substituting the profiles increases the maximum deflection under extreme load by a mere 0.0484 mm (an increase of only 0.66%). This negligible variation proves that the compensated DfA profile dimensions have no adverse impact on the global structural stiffness of the ship girder, confirming the practical feasibility of making ship designs "robot-ready."

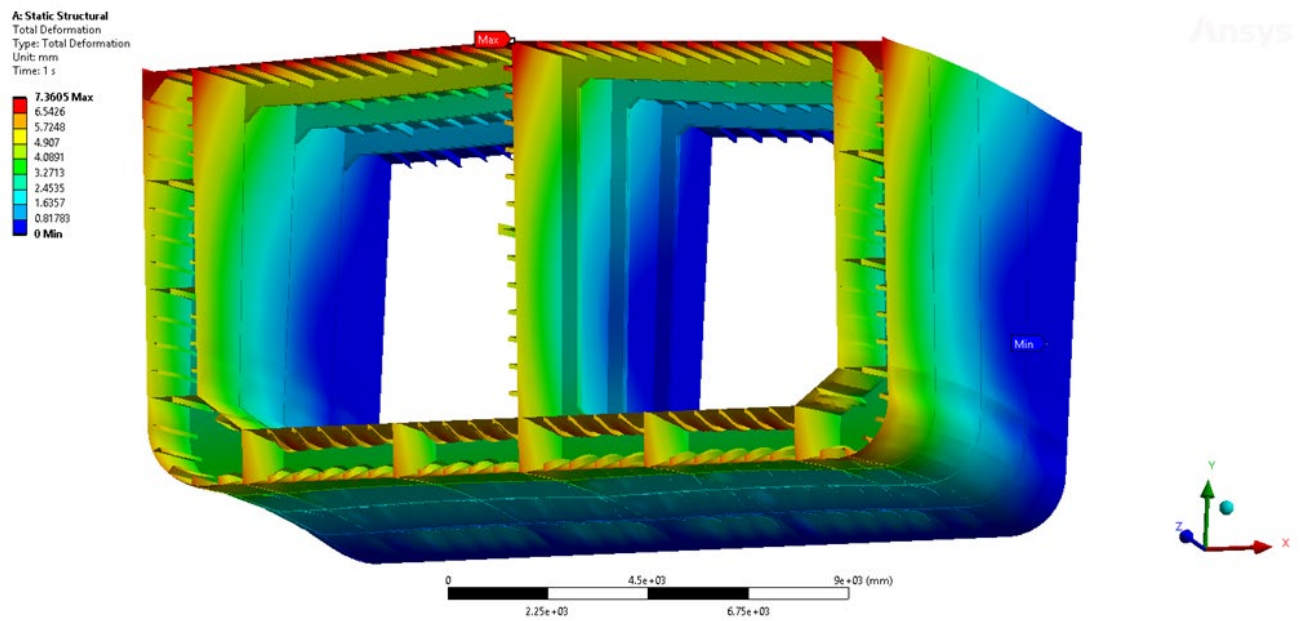
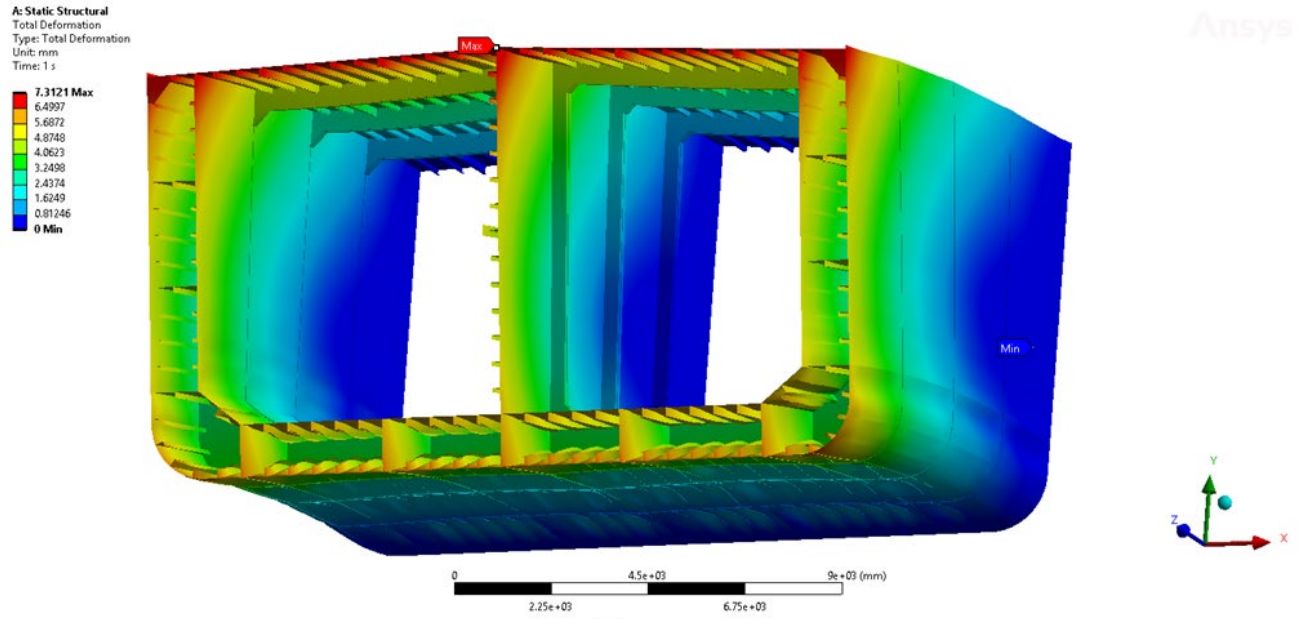


Figure 6-19 Comparison of total structural deformation contours: (a) initial baseline design, and (b) DfA-compliant design under identical loading conditions.

6.7 Discussion

6.7.1 Geometric Constraints and Robotic Kinematics

The primary challenge identified in this study is the extreme mismatch between the robot's standard kinematic reach and the ultra-confined 1.2m height of the ship's double-bottom structure. The results demonstrate that while the IRB 1200 has a nominal reach of approximately 700mm–900mm, nearly 40% of its theoretical workspace is "truncated" by the overhead inner bottom plate and longitudinal stiffeners. This truncation forces the robot into "singular" configurations where the joints must rotate near their mechanical limits to maintain the welding torch angle, significantly increasing the risk of axis-specific collisions (Andersen et al., 2016).

6.7.2 Technical Failure of the Inverted Configuration

The failure of the inverted configuration provides a critical insight into "confined space robotics." Although an inverted mount is often used in automotive plants to save floor space, in a 1.2m ship bay, it creates a "deep-reach" problem. To weld a fillet joint on the bottom plate, the robot must extend its arm downward. This extension aligns Axis 3 and Axis 4 in a way that the "elbow" volume protrudes horizontally, leading to unavoidable collisions with the vertical stiffener webs. This confirms that inverted mounting is only viable in ship structures with much larger vertical clearances or for overhead welding tasks only (Morgado-Estevéz et al., 2018).

6.7.3 Mobility and Accessibility Trade-off

A key finding is the trade-off between weld accessibility and transversal mobility.

- **Accessibility:** The floor-mounted position offers the most stable welding environment but turns the robot into a "static cell". In a shipyard context, this would require frequent, time-consuming manual crane lifts to move the robot between hundreds of compartments.
- **Mobility:** The elevated (on stiffener) position suggests a "mobile robot" paradigm. By using the stiffener as a rail, the robot could theoretically traverse multiple bays autonomously. However, the current simulation shows that raising the robot base by 130mm–200mm (the height of the stiffener) places Axis 3 in direct conflict with the inner bottom longitudinal during the return or home-stroke transitions.

6.7.4 Industrial Relevance of the Closed Block Phase

The findings of this chapter are particularly relevant when considering the transition from an open-frame environment to a closed block assembly. While gantry-based robotics are highly effective for open blocks, they are physically incapable of reaching internal joints once the deck or side shells are in place. This creates a high demand for compact manipulators that can be deployed within the 1.2m double-bottom height to perform the U-shaped welding line.

The "High" collision risk identified in the inverted configuration is especially problematic during this stage, as the robot must navigate a "forest" of longitudinal stiffeners to reach the bottom plate. Similarly, the elevated position, while efficient for movement, must account for the narrow slits and structural boundaries formed after the block is "put to the slit" during assembly. By validating these paths in a DTP, shipyards can avoid the costly and dangerous "trial-and-error" approach traditionally associated with manual welding in these enclosed areas (Y. G. Lee et al., 2020).

6.7.5 Implications for "Design for Automation"

The recurring collisions observed in the elevated position strongly suggest that the current standard ship geometry is the bottleneck for automation (Wahidi et al., 2024). The data indicates that even a high-performance manipulator like the IRB 1200 cannot overcome the physical limitations of a 1.2m height if the stiffeners remain at their current dimensions.

Consequently, this study identifies a critical need to transition from "Designing for Manual Welding" to "Designing for Robotic Automation" (Aydin et al., 2020). While this paper focuses on identifying these kinematic bottlenecks through a Digital Twin Prototype (DTP), it lays the groundwork for future structural adjustments (Mursid et al., 2025). Modifying the stiffener profile (e.g., reducing height or altering flange width) could provide the necessary few centimetres of clearance that would turn a "collision-prone" path into a "collision-free" autonomous movement.

6.7.6 Synthesis of the Design for Automation (DfA) Framework and Structural Co-Design

The integration of the proposed Design for Automation (DfA) framework within the structural design of the 7,700 DWT product tanker represents a critical milestone in bridging the gap between kinematic simulation and practical naval architecture. Traditionally, ship structural design and robotic path planning are executed as isolated engineering tasks. This disconnected approach inevitably creates "kinematic dead zones" where standard industrial manipulators cannot operate due to structural boundaries (Bonnin-Pascual & Ortiz, 2019). By establishing a co-design methodology,

this study demonstrates that ship compartments can be made "robot-ready" while fully preserving structural safety under extreme sea loads.

The baseline kinematic analysis highlighted a critical bottleneck: the 1200 mm double-bottom compartment height, combined with conventional 200 mm web-height stiffeners, leaves only 800 mm of vertical clearance. This spatial compression forces the robot's Axis 3 (elbow) joint into unavoidable, recurring collisions with the overhead deck stiffeners. By substituting these baseline profiles with off-the-shelf, commercial profiles, specifically a 150 mm web height for the bottom longitudinals and a 100 mm web height for the inner bottom longitudinals, the physical clearance envelope is successfully expanded to the target 950 mm safety margin. This simple, market-ready geometric modification completely eliminates Axis 3 interference during autonomous transversal rail transit.

From a structural standpoint, reducing the web heights of the longitudinal stiffeners inherently reduces their local section modulus and load-carrying capacity. However, our Finite Element Analysis (FEA) confirms that compensating for this height reduction by increasing the profile thickness from 10 mm to 12 mm successfully maintains the structural integrity of the hull girder under combined service loads (including hydrostatic pressure, cargo loads, and global hogging moments).

The FEA stress and deformation results prove that the proposed DfA profile substitution does not compromise the global stiffness or load-bearing capability of the double bottom. Crucially, while the manual stiffener substitutions proposed in this study represent a direct, highly practical engineering solution, they reveal an outstanding opportunity for systematic structural optimisation considering DfA

constraints. Rather than relying on trial-and-error profile substitutions, future research will focus on developing advanced multi-objective mathematical optimisation algorithms (such as genetic algorithms or Pareto-front searches). This integration of structural optimisation with robotic workspace boundaries stands as the next logical step in fully realising the goals of Shipbuilding 4.0.

6.7.8 Research Limitations

Although this study establishes a robust structural-kinematic co-design methodology, several limitations remain. First, the virtual path-planning model (ABB RobotStudio) assumes idealised conditions, omitting physical cabling, welding harnesses, and wire-feeder footprints. Second, the structural FEA evaluates static service loads but excludes transient thermal deformations and welding residual stresses. Finally, while the governing parametric equations (Rules 1–3) are universally applicable, the specific geometric thresholds are calibrated for a 900 mm arm reach robot manipulator and a 7,700 DWT tanker. Scaling the framework to alternative robot kinematics or larger vessel designs will require recalibrating these localised clearance boundaries. Consequently, executing a systematic structural optimisation that directly integrates these kinematic DfA clearance constraints represents the immediate next step of our research.

Chapter 7. Robotic Welding Constraints in Multi-Objective Optimisation of Ship Double Bottom Blocks for Confined Space Applications

7.1 Chapter Outline

This chapter proposes a novel integrated framework that incorporates robotic welding constraints directly into the multi-objective structural optimisation of a ship's double bottom block. The primary novelty of this research lies in its integrated optimisation approach, which moves beyond simple weight minimisation. Unlike previous studies, this optimisation maintains a constant number of stiffeners to prevent excessive welding paths. This study implements a multi-objective optimisation strategy to simultaneously minimise weight and optimise structural scantlings. A key focus is the minimisation of web plate height, which serves a dual purpose: streamlining the welding procedure during double bottom assembly and expanding the functional working space required for robotic arm manoeuvres. This ensures that the structure is not only lightweight but also "robot-friendly" and efficient to produce, while strictly adhering to the permissible structural integrity limits. The study employs an ABB IRB 1200 robotic model as a reference for confined space manoeuvrability. This research aims to demonstrate that a "Robotic-Friendly" design can be achieved without compromising structural efficiency, providing a practical pathway for automated ship block assembly.

7.2 Methodology

The methodology begins by establishing the geometric model while analysing robotic welding parameters and reachability to ensure compatibility with automated production in confined spaces. This is followed by numerical pre-studies, including mesh convergence and baseline load analysis, to define optimisation variables. The core of the process employs a hybrid numerical approach, starting with a Design of Experiment (DoE) matrix (G. Guan, Xu, et al., 2025), followed by a Response Surface Method (RSM) with Central Composite Design (CCD) to create a high-fidelity surrogate model (B. Guan & Li, 2026), and finally utilising a Multi-Objective Genetic Algorithm (MOGA) to identify optimal candidates (S. Gao et al., 2026). The methodology concludes by evaluating candidates against weight, classification standards, and robotic accessibility through final Finite Element Analysis (FEA) validation to finalise the production-efficient structural configuration.

7.2.1 Problem Definition in Confined Structures

The primary challenge addressed in this study is visualised in Figure 6-1, which shows an authentic operational environment inside a ship's double bottom block. This area represents a typical 'confined space' in shipbuilding, characterised by low overhead clearance, complex internal geometry due to intersecting structural members (e.g., girders, solid floors, and stiffeners), and limited entry/exit points (manholes). These physical restrictions impose severe constraints on standard fabrication processes. Traditionally, welding in these zones requires highly skilled workers operating in ergonomic postures that are both hazardous and non-productive (Kandemir et al., 2019). Figure 6-1 serves as the baseline justification for the necessity

of integrating robotic welding feasibility as a prerequisite constraint in the structural optimisation framework, as manual intervention is extremely difficult and automated access is strictly governed by the localised spatial layout.

Structural design optimisation in shipbuilding is pivotal for enhancing fabricability, elevating life-cycle efficiency, and ultimately diminishing manufacturing expenditures (L. Sun & Wang, 2011). Significant research thrust within this domain concerns the design of localised structural constituents, such as stiffened panels, which constitute fundamental elements in marine vessel architecture (Wahidi et al., 2025). The adoption of a unit-panel methodology significantly accelerates production throughput, particularly for large-scale ships. Following the integration of these unit panels into a double-bottom assembly, a restrictive U-shaped boundary must be internally welded at the intersections of the inner and outer shells (Lee, 2013), as conceptualised in Figure 7-1. The highlighted yellow lines indicate the final fillet welds that secure the vertical web frames to the bottom panel. This process entails joining contacting interfaces between longitudinal stiffeners and transverse web floors, or between the upper and lower plates, typically confined within a spatial vertical distance of only 1.2 meters.

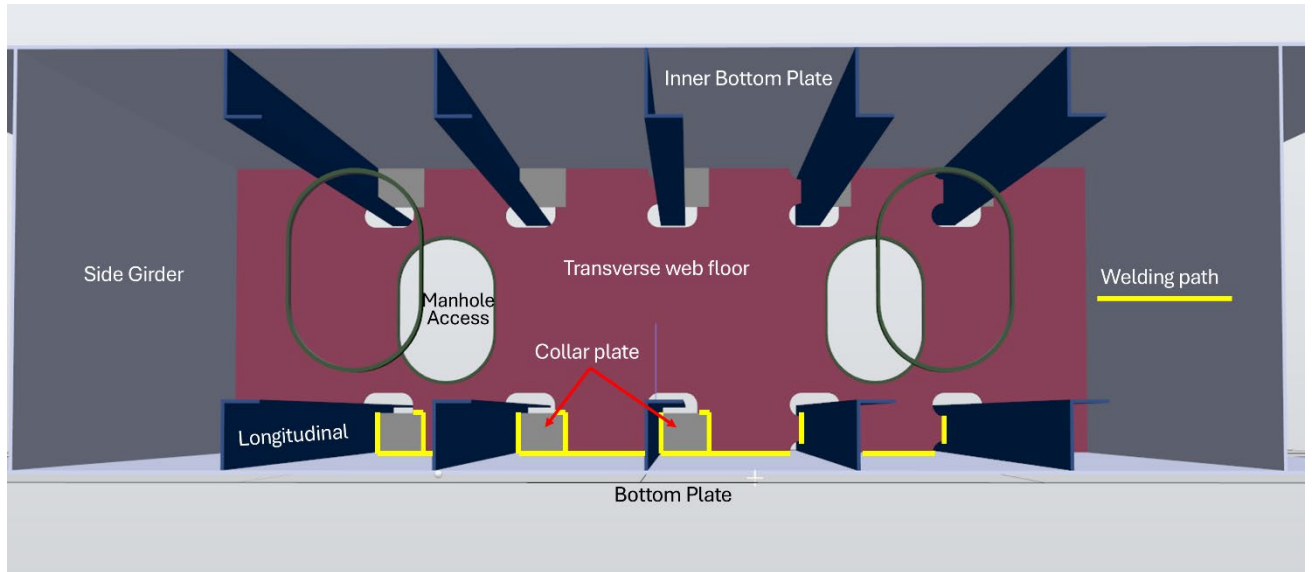


Figure 7-1 Schematic illustration and implementation of the U-shaped welding trajectory during the sub-assembly of a transverse web floor and bottom plate panel. The yellow lines indicate the continuous welding path, incorporating weaving motions, scallop welding manoeuvres, and torch orientation adjustments around the collar plate using a sequence of start, end, and via-points.

7.2.2 Parametric Geometric Modelling and Material Properties

The structural investigation is focused on a 7,700 DWT product tanker, characterised by a length overall (LOA) of 117 m, a moulded breadth (B) of 17.7 m, and a moulded depth (H) of 9.2 m. To ensure computational efficiency without compromising the structural integrity analysis, a representative segment of the midship parallel middle body was extracted for the finite element model. As illustrated in Figure 7-2 the longitudinal extent of the model encompasses a full compartment between two watertight bulkheads, which is equivalent to four times the solid floor spacing. This domain corresponds to a total length of 20 frame spacings, with a standard interval of 600 mm per frame spacing. This modelling approach was selected

to capture the characteristic structural response under global and local loading while accounting for the periodicity of the double bottom structure.

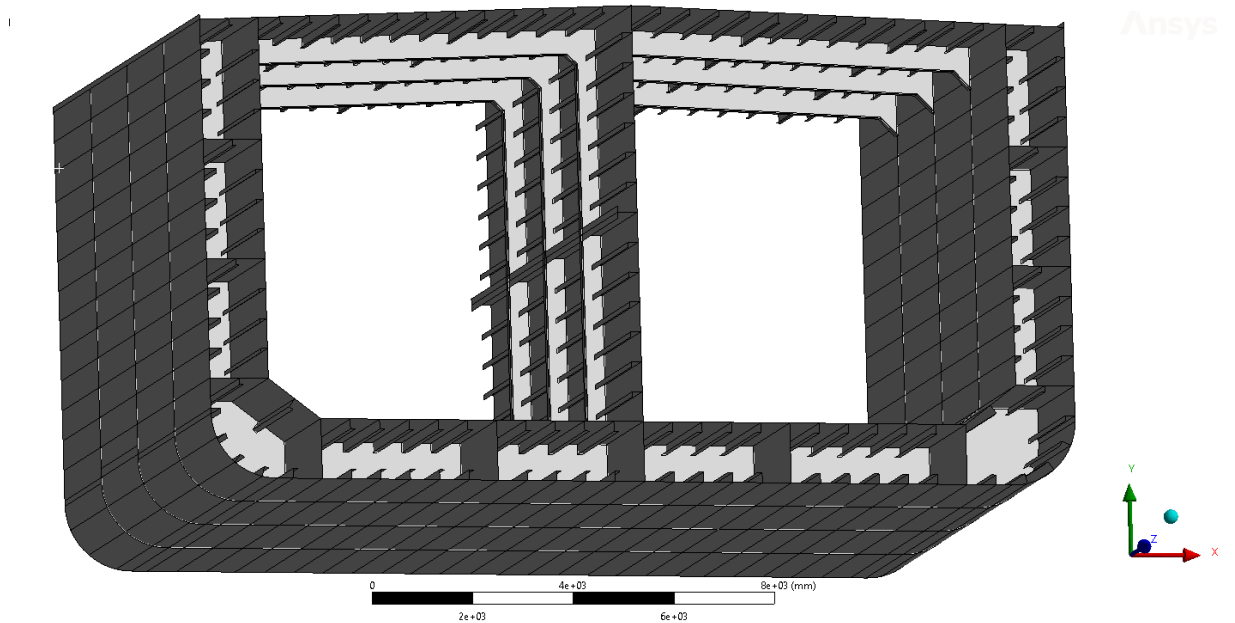


Figure 7-2 Extracted midship model for FEA analysis.

The primary design variables include the thicknesses of the keel, bottom and inner bottom plates, the web and the flange thickness, as well as the web height and flange width of the stiffeners. The material assigned is marine-grade structural steel with a yield strength (σ_y) of 235 MPa. The density is taken as 7850 kg/m³ with a Young's modulus of 200 GPa and a Poisson's ratio of 0.3.

The proposed structural optimisation framework is specifically applied to the ship's double bottom structure, which represents a critical domain characterised by extremely confined space conditions that impede automated fabrication. Unlike conventional studies that vary the number of stiffeners, this framework maintains a fixed number of longitudinal stiffeners to minimise total weld length and manufacturing complexity (Wahidi et al., 2025). The primary objective is to harmonise

localised manufacturability constraints, stemming from robotic operational envelopes, with traditional structural performance targets. Subsequently, to validate that the localised optimised design does not compromise the overall structural integrity, a comprehensive global structural analysis is performed on the complete midship section of the vessel. This multi-scale approach ensures that the newly derived structural configuration, while fulfilling local automated production requirements, maintains sufficient capability to safely withstand the global vertical bending moments and localised hydrostatic pressures encountered by the entire hull girder during its operational life cycle.

7.2.3 Systematic Collision Detection Strategy

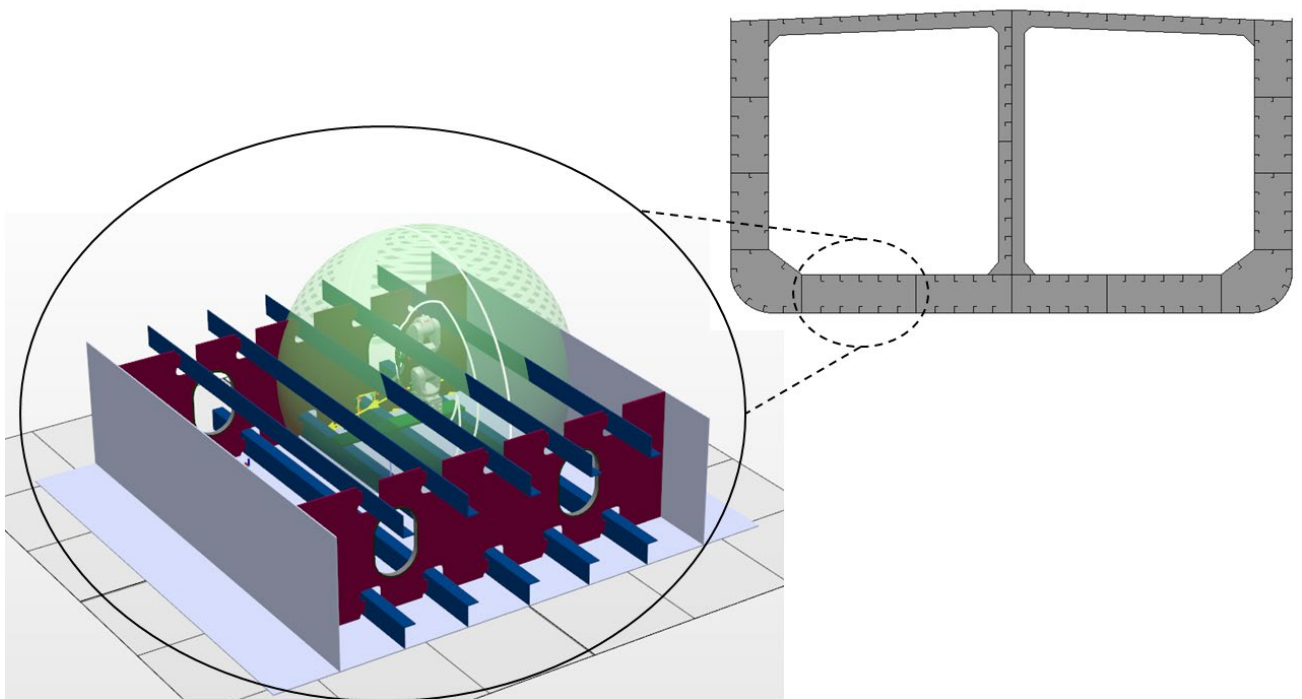


Figure 7-3 Double bottom structure 3D model for robotic constraint analysis.

To establish the initial robotic operational constraints, the first step in the methodology involved creating a high-fidelity 3D geometric model of a single, full-scale double bottom block, reflecting its actual dimensions as illustrated in Figure 7-3. Based on this baseline geometry, an iterative process was conducted to identify an appropriate industrial robot whose specifications and articulated dimensions were compatible with the restrictive cross-section of the mandatory manhole access openings. This prerequisite selection ensures that the chosen robotic system can physically enter and operate within the confined cells before any further structural optimisation or automated path planning simulations are performed.

To ensure complete coverage of potential collision risks within the restricted 1200 mm double bottom compartment, a systematic collision detection workflow was integrated between the dynamic kinematic simulation (ABB RobotStudio) and the optimisation algorithm (MOGA).

The identification of collision risks covers the full operational cycle of the welding robot, categorised into three distinct kinematic phases:

1. Approach Phase: Linear entry of the robot arm into the cell, where collision risks primarily occur between the upper robot link/elbow joint and the inner bottom longitudinal stiffeners (h_{w2}).
2. Execution Phase (Continuous U-Shaped Welding): Re-orientation and torch manipulation along the longitudinal stiffener web (h_{w1}) and bottom plate (t_b), where risks involve torch tip-to-corner interference and wrist assembly collision with stiffener flanges (b_{f1}, b_{f2}).

3. Retraction Phase: Reverse manoeuvring to clear the cell, where cross-sectional clearance is critical to prevent elbow joint interference with upper stiffeners under deflected robot postures.

7.2.4 Finite Element Analysis (FEA) Configuration

The initial design of the double bottom block was modelled based on the scantling requirements for a typical midship section. The structural configuration maintains a consistent arrangement of longitudinal and transverse members to evaluate the impact of scantling optimisation on robotic accessibility. Numerical simulations were performed using the Finite Element Method (FEM) to evaluate the structural response under operational loads. Shell elements were employed to model the thin-walled plates and stiffeners, ensuring computational efficiency without sacrificing accuracy in stress distribution (D. H. Kim & Paik, 2017).

- **Boundary Conditions:** The block edges were subjected to fixed support conditions using rigid remote displacement to simulate the continuity of the ship's hull.
- **Loading:** A combination of hydrostatic pressure, gravity loads, and vertical bending moment was applied to represent the maximum operational draft conditions.
- **Mesh Strategy:** To ensure the reliability of the finite element results, a systematic mesh convergence study was conducted by refining the element size from 500 mm to 50 mm. This procedure was essential to identify an optimal mesh density that balances numerical accuracy with computational efficiency.

7.2.4.1 Scantling and Material Properties

The baseline structure consists of bottom and inner bottom plating with initial thicknesses of 11 mm and 8 mm, respectively, reinforced by L-profile longitudinal stiffeners featuring a 200 mm web height, 100 mm flange width, and 10 mm thickness for both elements. Primary transverse and longitudinal strength is provided by plate floors and girders with a standard height of 1200 mm. The entire assembly is modelled using Marine Grade A steel with a yield strength of 235 MPa, which defines the allowable stress limit for this analysis as follows:

$$\sigma_{\text{all}} = \eta \times \sigma_y \quad (7.1)$$

where η is the usage factor, set at 0.75 for local structural analysis, resulting in a limit of 175 MPa (Lloyd's Register (LR), 2024).

7.2.4.2 Boundary Conditions and Remote Points

To accurately represent the structural behaviour of the block within the global hull context, a hybrid boundary condition approach was implemented:

1. Rear Section (Aft): As illustrated in Figure 7-4 a Remote Point was established at the neutral axis of the rear section. This point is configured with a Remote Displacement using Fixed Behaviour (Rigid). This setup effectively represents the high stiffness of a transverse bulkhead, preventing local cross-sectional distortion while constraining all degrees of freedom ($UX, UY, UZ, ROTX, ROTY, ROTZ = 0$).
2. Front Section (Forward): A remote point was applied to the forward cross-section. To simulate the most critical longitudinal strength requirement, a Hogging

Bending Moment (M_h) was applied to this point. This condition induces tension in the deck (or inner bottom) and compression in the bottom shell, representing the global longitudinal stress acting on the block (Lima et al., 2025).

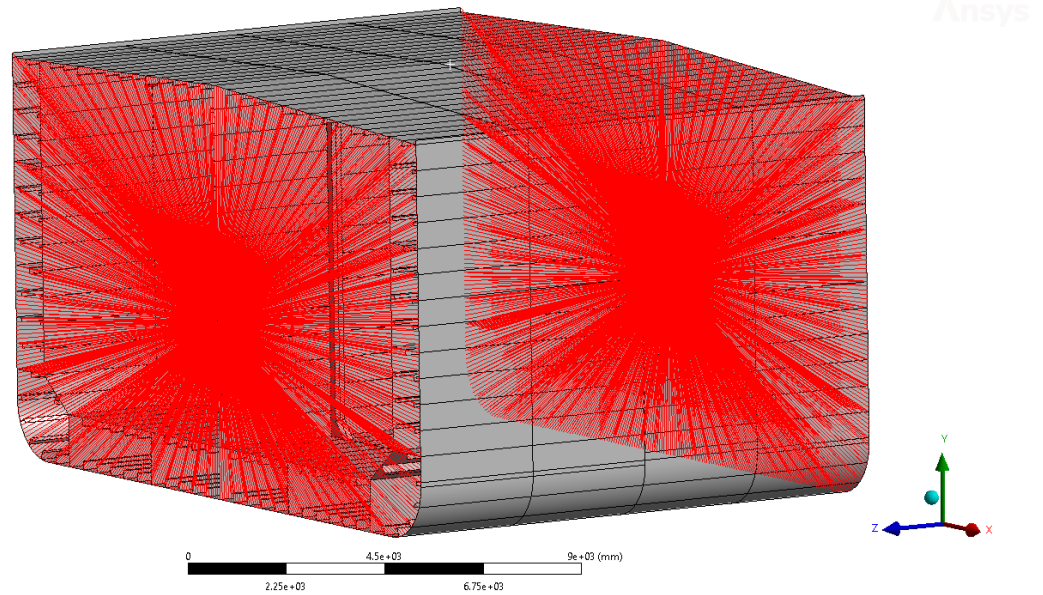


Figure 7-4 Application of global hull girder loads. A dedicated Remote Displacement is defined at the neutral axis to apply the vertical bending moment, ensuring a linear distribution of longitudinal stresses across the section, balanced against a fixed support.

7.2.4.3 Loading Conditions

The model is subjected to simultaneous environmental and operational loads to represent a "Worst-Case" scenario as illustrated in Figure 7-5:

- External Hydrostatic Pressure (P_{ext}): Representing the seawater pressure acting on the bottom shell and side shells. The pressure is calculated as:

$$P_{ext} = \rho_s \cdot g \cdot (z_w - z) \quad (7.2)$$

where ρ_s is seawater density (1025 kg/m³), g is gravity, z_w is the waterline height, and z is the vertical coordinate.

- Internal Cargo Pressure (P_{int}): Representing the hydrostatic load of liquid cargo (oil) inside the tank.
- $P_{int} = \rho_c \cdot g \cdot (z_c - z)$ (7.3)

where ρ_c is cargo density (745 kg/m³) and z_c is the filling height of the tank.

- Standard Earth Gravity: A global acceleration of 9.81 m/s² is applied to account for the self-weight of the steel structure.

In the initial structural assessment, the hogging bending moment was selected as the primary loading condition. This decision is based on the operational reality that hogging typically represents the most frequent and severe global stress state for most ship types, particularly when the midship region is subjected to high buoyancy or concentrated cargo loads at the ends. By prioritising the hogging condition, the optimisation process addresses the most demanding structural requirements encountered during the vessel's service life (D. H. Kim & Paik, 2017).

Subsequently, to ensure the robustness of the optimised scantlings, a verification phase was conducted by applying the sagging bending moment. This dual-condition verification ensures that the reduced weight and minimised web height do not compromise the structural integrity when the stress state is reversed, particularly concerning the buckling stability of the inner bottom plating.

According to the Lloyd's Register (LR) Rules for Ships, the design vertical wave bending moment at any hull section is calculated to ensure the vessel can withstand environmental dynamic loads. The hogging wave bending moment ($M_{w,h}$) is determined using the following empirical formula:

$$M_{w,h} = +0.19 \cdot C \cdot L^2 \cdot B \cdot C_b \quad (\text{kN.m}) \quad (7.4)$$

where:

- L: Rule length of the ship (meters).
- B: Moulded breadth of the ship (meters).
- C_b : Block coefficient at the design draught.
- C: Wave parameter (Wave Coefficient), typically defined as:

$$\circ \text{ For } 90 \leq L \leq 300 = 10.75 - \left[\frac{300-L}{100} \right]^{1.5} \quad (7.5)$$

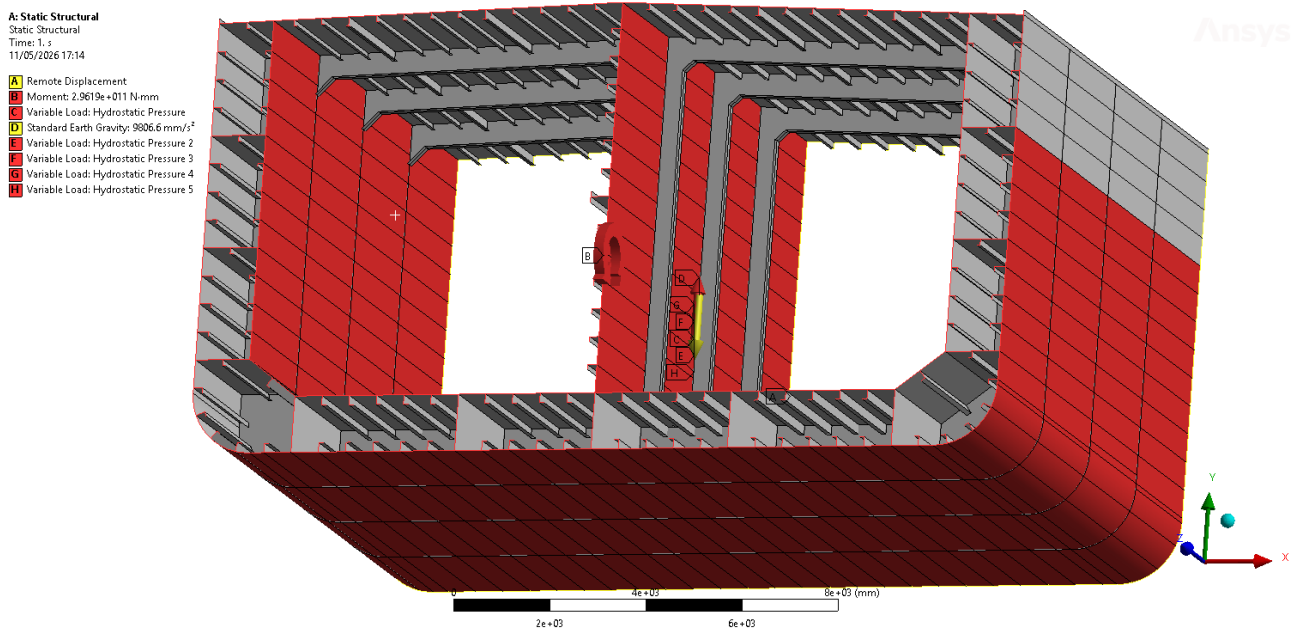


Figure 7-5 Boundary conditions and loading scenario applied to the midship section. The model incorporates (A) Remote Displacement for global constraints, (B) a vertical bending moment of 2.96×10^{11} N.mm to simulate hull girder hogging, (C-H) hydrostatic pressure distribution acting on the submerged hull shell and oil cargo pressure, and (D) standard Earth gravity for self-weight structural analysis.

7.2.4.4 Mesh Convergence Study

To ensure the independence of the numerical results from the spatial discretisation, a comprehensive mesh convergence study was performed by varying the element size from 500 mm down to 50 mm. As summarised in Table 7-1, the

maximum total deformation was utilised as the primary convergence metric, representing the global structural energy response.

Table 7-1 Mesh sensitivity analysis for structural response validation.

Element size (mm)	Density	No of Element	Nodes	Element Quality	Max Deformation (mm)	Relative error
500	0.0020	16561	17910	0.6912	7.2338	
400	0.0025	21722	23662	0.78135	7.2375	0.051%
200	0.0050	55460	59259	0.92564	7.2414	0.054%
150	0.0067	94947	100254	0.95699	7.2430	0.022%
100	0.0100	197329	205588	0.98273	7.2439	0.012%
75	0.0133	352534	363531	0.98538	7.2443	0.006%
50	0.0200	763191	779678	0.99283	7.2446	0.004%

The convergence of the finite element model was validated by plotting the maximum total deformation against the inverse of the element size, defined as Mesh Density (h^{-1} , where h is the element length in mm). As illustrated in Figure 7-6, the maximum deformation rapidly stabilises as the mesh density increases beyond 0.0050 mm^{-1} . The selected mesh density of 0.010 mm^{-1} ($h = 100$ mm) provides a fully converged solution with a relative error of less than 0.02% compared to the finest mesh density of 0.020 mm^{-1} .

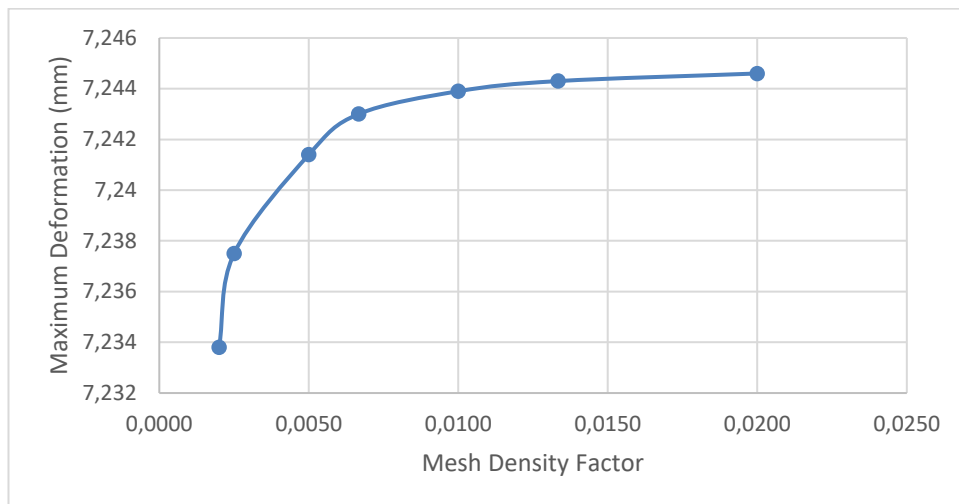


Figure 7-6 Mesh sensitivity plot : Mesh density factor (mm^{-1}) vs Maximum deformation.

The results indicate that the structural response reaches an asymptotic state as the mesh density increases. A significant reduction in the relative error is observed as the grid is refined; at a mesh density of 0.01 mm^{-1} (equivalent to a 100 mm element size), the relative error in maximum deformation plummeted to 0.012%. Further refinement to 50 mm (0.02 mm^{-1} density) yielded a negligible change of only 0.004%, while exponentially increasing the computational cost to 763,191 elements, as shown in Figure 7-7. Consequently, the 100 mm mesh size was selected as the optimal baseline for the subsequent multi-objective optimisation procedure. This selection provides a high-fidelity numerical solution with an excellent average element quality of 0.98, while maintaining computational efficiency for the recursive optimisation iterations.

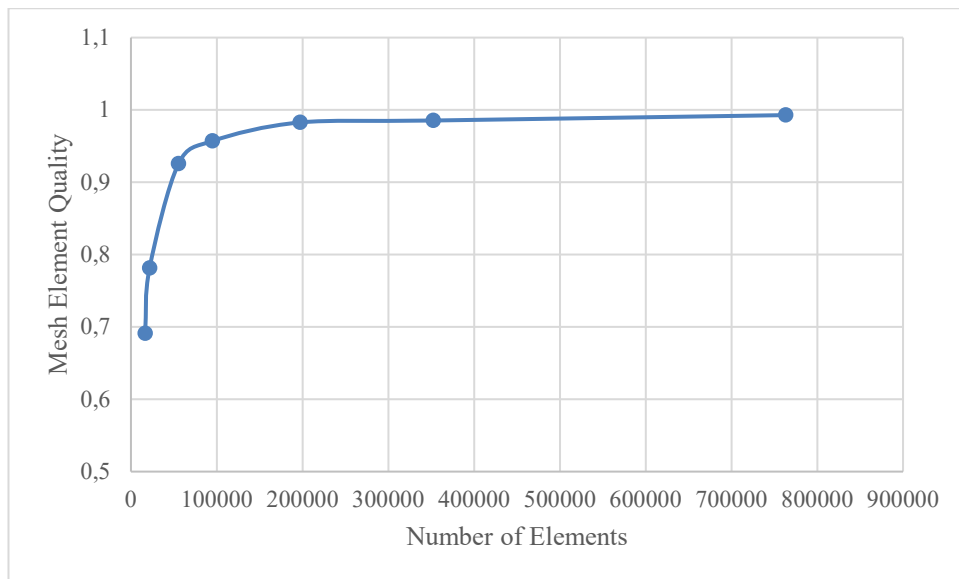


Figure 7-7 Mesh sensitivity plot: Number of elements vs. mesh element quality.

7.2.5 Structural Design Parameters and Optimisation Variables

The optimisation process begins with an initial scantling configuration, referred to as the "Initial Design," which serves as the baseline for performance comparison.

This design follows the standard structural arrangements for a double bottom block. To explore the design space efficiently, specific structural members were designated as design variables with defined discrete and continuous ranges.

Table 7-2 Scantling specifications of the initial design and the range of design variables for optimisation.

Component	Parameter	Initial Design (mm)	Design Variable Range (mm)	Type
Plating	Keel Plate Thickness (t_k)	13	6, 8, 10, 12, 14, 16	Discrete
	Bottom Plate Thickness (t_b)	11	4, 6, 8, 10, 12, 14	Discrete
	Inner Bottom Thickness (t_{ib})	8	4, 6, 8, 10, 12, 14	Discrete
Bottom Longitudinal	Flange Width (w_{fl})	100	90, 100, 110, 120, 130, 140	Discrete
	Flange Thickness (t_{fl})	10	6, 8, 10, 12, 14, 16	Discrete
	Web Height (h_{wl})	200	100 – 200	Continuous
	Web Thickness (t_{wl})	10	6, 8, 10, 12, 14, 16	Discrete
Inner Bottom Longitudinal	Flange Width (w_{f2})	100	60, 70, 80, 90, 100, 110	Discrete
	Flange Thickness (t_{f2})	10	6, 8, 10, 12, 14, 16	Discrete
	Web Height (h_{w2})	200	50 – 100	Continuous
	Web Thickness (t_{w2})	10	6, 8, 10, 12, 14, 16	Discrete

As summarised in Table 7-2, the variables include plate thicknesses and the geometric dimensions of the longitudinal stiffeners. Notably, the Web Height for both bottom and inner bottom longitudinal is treated as a continuous variable within a specified range to accommodate the precise spatial requirements for robotic welding accessibility. The sampling of these variables was conducted using a Central Composite Design (CCD) with a Face-Centered configuration, ensuring that the design points are located at the centre of the faces of the cubical design space, which is highly effective for estimating the interaction effects between scantling parameters (Montgomery, 2017).

To systematically explore the design space and calibrate the response surface approximations, a Design of Experiments (DOE) sampling scheme was executed across the bounded structural parameters. This sampling strategy generated a total of 151 distinct design points, distributed to capture nonlinear interactions between stiffener scantling variations and the corresponding structural responses. Evaluating these 151 discrete candidate configurations provided a robust, space-filling dataset that ensured sufficient fidelity across the surrogate response surface model prior to executing the multi-objective genetic algorithm (MOGA) optimisation phase.

7.2.6 Multi-Objective Optimisation Framework

The optimisation problem is formulated to resolve the conflict between weight minimisation and manufacturing accessibility (Sekulski, 2010). The Multi-Objective Genetic Algorithm (MOGA) was selected due to its robustness in searching the global design space (Lima et al., 2025).

Objective Functions:

1. Minimise Total Mass (W)
2. Minimise Web Plate Height (H_w) to streamline the welding process inside ship double bottom.

Constraints:

1. Maximum Equivalent Stress (σ_{eq}) $\leq$ 175 MPa (Allowable Stress)
2. Total Deformation (δ) $\leq$ Classification regulation limit
3. Minimum Robotic Clearance (C_r) based on robotic welding simulation results.

The optimisation framework integrates a robust sequence comprising Design of Experiments (DoE), Response Surface Methodology (RSM) (Myers et al., 2016), and

a Multi-Objective Genetic Algorithm (MOGA) (Guha et al., 2015). Initially, a Central Composite Design (CCD) was implemented to systematically generate representative input data (Cong et al., 2025). RSM was subsequently employed as a surrogate modelling tool to establish the mathematical and statistical correlations between design variables and system responses, including both objective functions and constraints (Myers et al., 2016). By constructing these predictive surfaces, the relationship between structural scantlings and performance outputs is effectively mapped, providing a reliable foundation for the genetic optimisation phase (Guerra et al., 2024).

The multi-objective optimisation reveals a clear competing relationship between minimising total structural mass (f_1) and minimising the combined longitudinal web height ($f_2 = h_{w1} + h_{w2}$). Reducing the web height directly enhances vertical working clearance (C_{robot}) for the robotic manipulator. However, a reduction in web height decreases the bending stiffness (section modulus) of the longitudinal members. To satisfy the maximum stress constraint ($\sigma_{\text{max}} \leq 175 \text{ MPa}$), MOGA compensates for shorter web heights by selecting thicker flange scantlings (t_f) or thicker bottom plating (t_b). Consequently, designs prioritising maximum working clearance incur a slight mass penalty, whereas designs prioritising minimum structural mass push stiffener heights closer to the constraint boundary. The MOGA framework generates a well-distributed Pareto front, allowing designers to select a candidate solution that guarantees required robotic clearance while maintaining optimal weight efficiency.

7.2.7 Mathematical Formulation of the Optimisation Problem

To resolve the trade-off between structural weight efficiency and automated welding accessibility, the optimisation problem is formulated as a Multi-Objective Optimisation (MOO) problem solved using a Multi-Objective Genetic Algorithm (MOGA).

7.2.7.1 Design Variables

The set of design variables $\mathbf{x}$ consists of the structural scantlings of the double bottom block, defined as:

$$\mathbf{x} = \{t_k t_b, t_{ib}, h_{w1}, t_{w1}, b_{f1}, t_{f1}, h_{w2}, t_{w2}, b_{f2}, t_{f2}\} \quad (7.6)$$

where t_b and t_{ib} represent the plate thicknesses of the outer bottom shell and inner bottom plating, respectively; $h_{w1}, t_{w1}, b_{f1}, t_{f1}$ denote the web height, web thickness, flange width, and flange thickness of the bottom longitudinal stiffeners; and $h_{w2}, t_{w2}, b_{f2}, t_{f2}$ denote the corresponding scantling dimensions for the inner bottom longitudinal stiffeners.

7.2.7.2 Objective Functions

The optimisation aims to simultaneously minimise the structural mass and the total vertical depth occupied by the stiffeners to maximise the working space inside the double bottom compartment. The objective vector $\mathbf{f}(\mathbf{x})$ is defined as:

$$\min_{\mathbf{x}} \mathbf{f}(\mathbf{x}) = \{f_1(\mathbf{x}), f_2(\mathbf{x})\} \quad (7.7)$$

1. Mass Minimisation ($f_1(\mathbf{x})$):

$$f_1(\mathbf{x}) = W(\mathbf{x}) = \rho_s \sum_{i=1}^{N_e} V_i(\mathbf{x}) \quad (7.8)$$

where $W(\mathbf{x})$ is the total mass of the ship double bottom block, ρ_s is the density of Marine Grade A steel (7850 kg/m³), V_i is the structural volume of element i , and N_e is the total number of finite elements.

2. Combined Web Height Minimisation ($f_2(\mathbf{x})$):

$$f_2(\mathbf{x}) = h_{w,\text{total}} = h_{w1} + h_{w2} \quad (7.9)$$

Minimising the combined height of the bottom and inner bottom longitudinal webs ($h_{w1} + h_{w2}$) directly maximises the vertical clearance available for robotic maneuvering.

7.2.7.3 Constraint Formulations

The optimisation is subjected to structural integrity, classification rule limits, and robotic manoeuvrability constraints:

1. Maximum Allowable Stress Constraint:

$$g_1(\mathbf{x}) = \sigma_{\max}(\mathbf{x}) - \sigma_{\text{allowable}} \leq 0 \quad (7.10)$$

where $\sigma_{\max}(\mathbf{x})$ is the maximum Von Mises stress evaluated from FEA, and $\sigma_{\text{allowable}} = 175$ MPa according to IACS CSR standards.

2. Total Structural Deformation Constraint:

$$g_2(\mathbf{x}) = \delta_{\max}(\mathbf{x}) - \delta_{\text{allowable}} \leq 0 \quad (7.11)$$

where $\delta_{\max}(\mathbf{x})$ is the maximum resultant displacement, and $\delta_{\text{allowable}}$ is the maximum permissible deflection governed by classification society rules.

3. Robotic Clearance and Collision Avoidance Constraint:

Where $H_{DB} = 1200$ mm represents the net internal height of the double bottom compartment, the effective vertical clearance $C_{robot}(\mathbf{x})$ between the opposing longitudinal stiffeners is defined as:

$$C_{robot}(\mathbf{x}) = H_{DB} - (h_{w1} + h_{w2}) \quad (7.12)$$

To guarantee a zero-collision operational envelope during the full U-shaped welding path, C_{robot} must satisfy the minimum required clearance threshold ($C_{req} = 950$ mm), as established by the robotic welding simulation results shown in Figure 6-16:

$$g_3(\mathbf{x}) = C_{req} - C_{robot}(\mathbf{x}) \leq 0 \quad \text{where } C_{req} = 950 \text{ mm} \quad (7.13)$$

4. Geometric Bounds:

$$\mathbf{x}_{lower} \leq \mathbf{x} \leq \mathbf{x}_{upper} \quad (7.14)$$

where $\mathbf{x}_{lower}$ and $\mathbf{x}_{upper}$ represent the lower and upper physical boundary limits for each design variable, respectively, ensuring that the optimised scantlings remain practically manufacturable and aligned with standard commercial steel plate dimensions.

7.3 Results and Validation

7.3.1 Robotic Welding Criteria

The integration of robotic automation in confined ship structures necessitates a precise definition of operational constraints based on both vessel geometry and robotic kinematics. To ensure the feasibility of the automated welding process, the selection of the robotic system was initially constrained by the accessibility of the double bottom compartments. Standard manholes in double bottom blocks, typically measuring 600 x 400 mm for a 1200 mm height configuration, serve as the primary entry points for

the equipment (Jeong et al., 2018). To optimise manoeuvrability and reduce setup time, the robotic base is strategically positioned atop the longitudinal stiffeners. This "stiffener-mounted" positioning is adopted to facilitate smoother linear transitions between welding zones and to overcome the floor-level obstructions common in double bottom assemblies (Lee et al., 2008). Furthermore, the robot's "reachability" or workspace envelope was analysed to minimise the frequency of base relocations. By maximising the reach area from a single stationary point, the system ensures continuous U-shaped welding paths, which are vital for maintaining weld quality and reducing production cycles.

To maximise welding efficiency within the confined double bottom compartments, a comparative reachability analysis was conducted, as illustrated in Figure 7-8. The choice of robotic manipulator specifications is governed by the ability to cover the maximum weld length from a single stationary base position, thereby minimising non-productive relocation cycles.

- Left Configuration (Limited Reach): Represents a smaller manipulator with a restricted workspace. As shown, the reach envelope cannot fully encompass the longitudinal welding lines between two transverse floors, necessitating frequent repositioning of the robot base to complete a single U-shaped welding path.
- Right Configuration (Optimised Reach - 0.9 m): By utilising a robot with a 0.9 m reach radius (e.g., ABB IRB 1200), the operational envelope effectively covers the entire target welding zone within the compartment.

The 0.9 m reach capability allows the robot to execute the full "U-shaped" welding sequence, securing the longitudinal stiffeners to the bottom floor, without

requiring intermediate base movement. This optimisation significantly reduces the total manufacturing lead time and minimises the risk of alignment errors during base relocation. Furthermore, this reach specification ensures that the robot can access critical corner joints even when mounted atop the stiffeners to maintain clearance from the bottom plate.

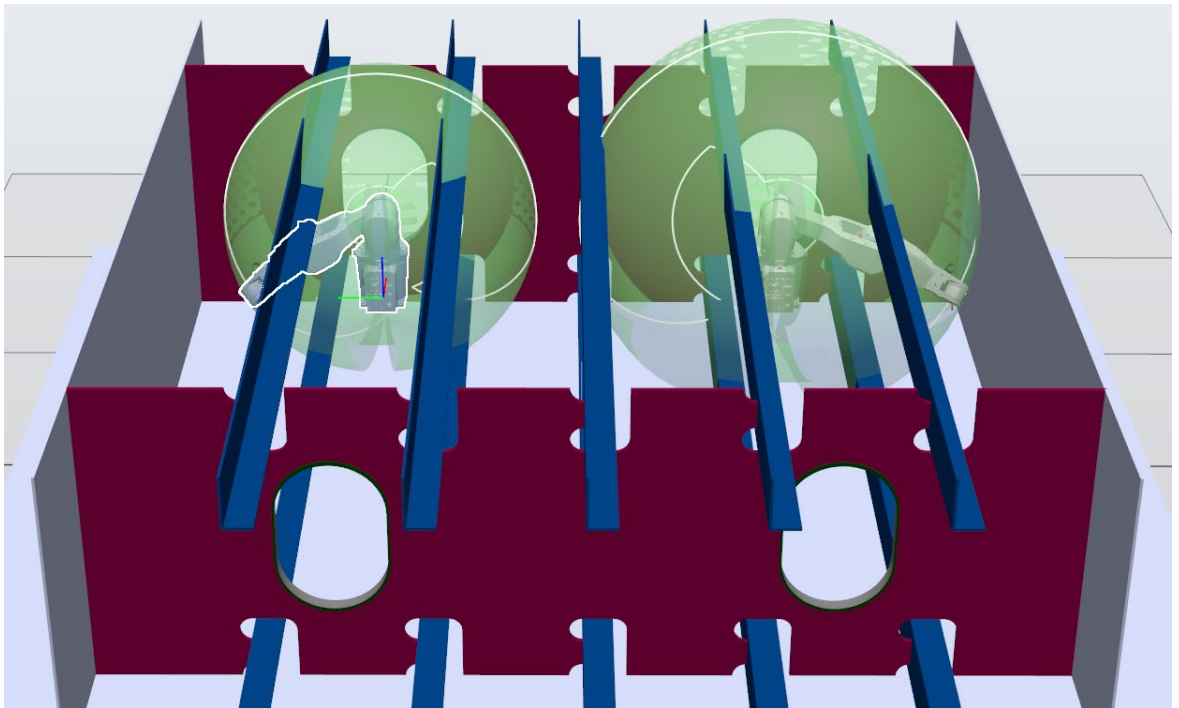


Figure 7-8 Workspace envelope evaluation within the double bottom compartment. The 0.9 m reach radius (right) minimises non-productive relocation cycles by providing comprehensive access to the longitudinal-to-floor welding joints.

Based on these spatial and operational requirements, the ABB IRB 1200 was selected as the reference robotic manipulator. This model offers a compact footprint and a reach of approximately 900 mm, making it ideal for the restricted 1200 mm height of the double bottom block. The physical dimensions and joint limits of the IRB 1200 were subsequently translated into numerical constraints within the optimisation

algorithm, specifically to define the minimum permissible web height (H_w) that avoids mechanical interference during the welding process.

The distinctive feature of this methodology is the inclusion of robotic manoeuvrability as a hard constraint. An ABB IRB 1200 robotic arm was utilised as the reference system for the welding tasks. The working envelope of the robot necessitates a minimum vertical and horizontal clearance within the double bottom compartments. A minimum threshold for robotic clearance was established to ensure the welding torch can achieve the required U-shaped welding path without colliding with the inner bottom plate or adjacent stiffeners (Lee et al., 2010).

7.3.2 Robotic Welding Simulation and Accessibility Constraints

7.3.2.1 Welding Robot Simulation

The integration of robotic operations within the double bottom block was evaluated through a high-fidelity simulation using ABB RobotStudio, as presented in Figure 7-9. The simulation environment replicates the actual geometric constraints and confined space conditions of a ship's double bottom structure. While the welding paths and robot arm kinematics were optimised based on the robot's specific reach and manoeuvrability, the digital signal logs recorded two distinct collision events. These collisions occurred during the transition from the initial home position to the welding start point and again during the retraction phase to the home position after completing the weld.

These findings highlight a critical research gap: conventional structural designs, even when modelled at full scale, do not inherently account for the dynamic swept volume of a robotic manipulator. The recorded collisions emphasise that achieving a

collision-free operation in such restricted environments requires more than just path planning; it necessitates a fundamental modification of the structural environment itself. Consequently, this observation serves as the primary motivation for including robotic accessibility, specifically the minimum clearance height, as a key constraint in the multi-objective structural optimisation framework. By increasing the web height clearance, the risk of mechanical interference can be eliminated, ensuring the feasibility of automated welding processes in maritime manufacturing.

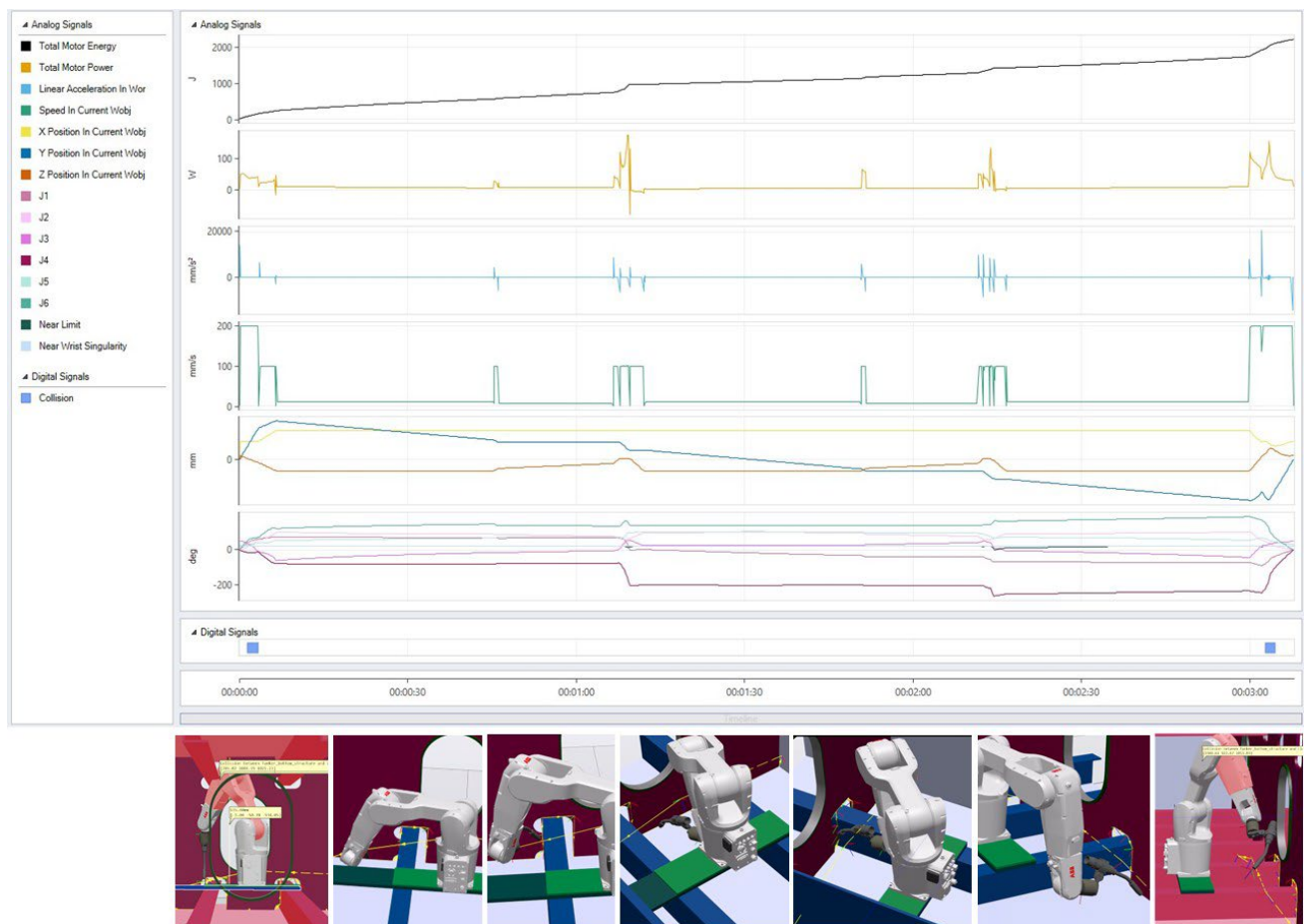


Figure 7-9 Simulation results of the robotic welding process within the double bottom confined space using ABB RobotStudio. The analogue signal charts track the motor energy, power, and joint kinematics, while the Digital Signals (bottom row) identify

two collision instances during the approach and retraction phases. The captured frames illustrate the robot's posture and the narrow clearance that led to the identified research gap.

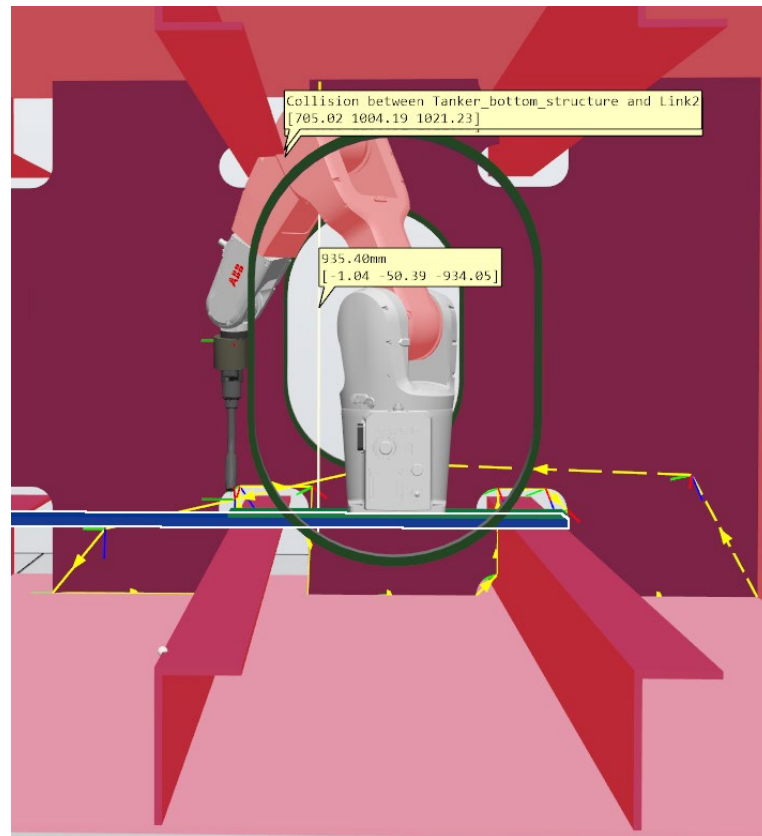


Figure 7-10 Robotic accessibility and collision detection analysis within the double bottom confined space. The simulation identifies the minimum required clearance, including a safety margin, to prevent contact between the robotic arm (Link 2) and the structural components.

To ensure the manufacturability of the optimised design, a robotic operational constraint was integrated into the structural optimisation framework. As illustrated in Figure 7-10, a 3D simulation was performed to evaluate the accessibility of an ABB

industrial robot within the confined cells of the double bottom. The simulation specifically monitored potential contact points between the structural members (girders, floors, and longitudinals) and the robotic arm links. Based on the collision detection analysis, a minimum clearance height of 950 mm was established. This value incorporates the physical dimensions of the robot at its maximum required articulated posture plus a safety operational margin. Any design candidate with a double bottom height or manhole opening that violates this 950 mm threshold is automatically classified as 'infeasible' in the multi-objective genetic algorithm (MOGA), as it would prevent automated welding operations in the production phase.

7.3.2.2 Justification of Objective Selection and Constraint Strategy

To systematically enforce collision avoidance, the full dynamic swept volume of the ABB IRB 1200, accounting for joint motion limits, torch holder dimensions, and safety margin, was extracted. The governing bottleneck was identified as the maximum vertical reach of the robotic arm during its continuous U-shaped transition between bottom and top stiffeners. This physical envelope dictates that a minimum net vertical distance of 950 mm (C_{req}) must exist between opposing stiffener flanges ($h_{w1} + h_{w2}$).

By mathematically defining this threshold in Constraint $g_3(\mathbf{x})$, candidate scantling configurations generated by MOGA that result in $C_{\text{robot}}(\mathbf{x}) < 950$ mm are automatically classified as infeasible and eliminated, thereby guaranteeing that all Pareto-optimal solutions achieve a verified zero-collision status.

A crucial distinction in the proposed optimisation framework lies between the mandatory robotic feasibility requirement and the performance optimisation metrics:

1. **Mandatory Robotic Feasibility (Constraint $g_3(\mathbf{x})$):** Robotic weldability cannot be treated merely as a flexible objective, as spatial interference results in physical collisions. Therefore, robotic clearance is enforced as a strict hard constraint ($C_{\text{robot}} \geq 950 \text{ mm}$). The 950 mm threshold synthesises multi-dimensional kinematic parameters, including torch orientation angles, dynamic arm swept volumes, and wrist assembly manoeuvrability evaluated during continuous U-shaped welding trajectories in ABB RobotStudio (Figure 7-10).
2. **Production Performance Optimisation (Objective $f_2(\mathbf{x})$):** Minimising the combined web height ($h_{w1} + h_{w2}$) as the second objective (f_2) is justified by its direct correlation with manufacturing efficiency. Shorter stiffener webs directly decrease the required fillet weld size, total weld metal deposition volume, and thermal distortion during block fabrication (Wahidi et al., 2025). Simultaneously, minimising h_w provides an expanded internal working envelope beyond the minimum 950 mm constraint, granting the robotic manipulator enhanced operational margin to accommodate potential fit-up tolerances during shipyard assembly.

7.3.3 Initial Structural Response

7.3.3.1 Stress Distribution and Critical Areas

The initial design, characterised by a uniform initial stiffener web height of 200 mm for both bottom and inner bottom longitudinals, was subjected to the combined design load (hydrostatic pressure and global hull girder bending). The maximum von Mises stress recorded was 145.46 MPa.

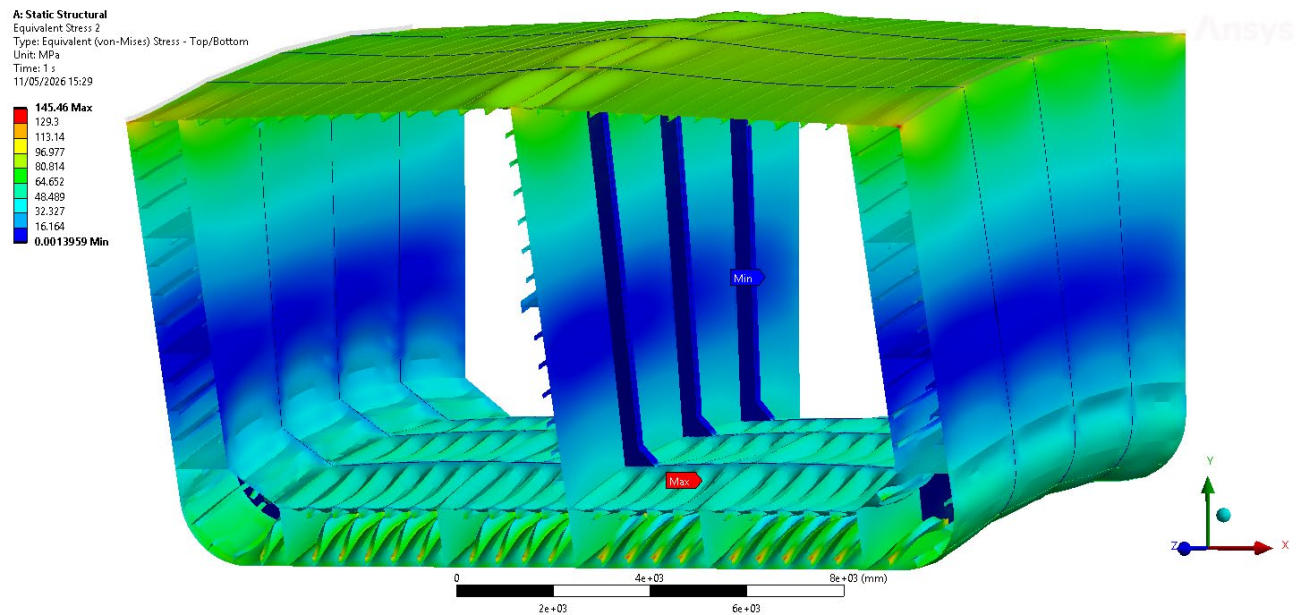


Figure 7-11 Von Mises stress distribution across the midship section under combined design loads, peaking at 145.46 MPa near the transverse bulkhead connection with a safety factor of 1.6 relative to the 235 MPa yield strength.

As illustrated in Figure 7-11, the high-stress regions are primarily concentrated at the connection points between the longitudinal stiffeners and the transverse floors. This phenomenon is expected due to the abrupt change in structural stiffness at these junctions, which induces localised shear and bending stresses. However, this peak value remains well below the permissible limit of 175 MPa ($0.75 \sigma_y$), indicating that the initial scantlings are structurally redundant and offer significant potential for weight and height reduction.

7.3.3.2 Global Deformation Characteristics

The global deformation profile of the initial midship structure under combined loading is illustrated in Figure 7-12. Based on the finite element analysis, the maximum total deformation was recorded at 7.2439 mm, primarily concentrated at the

upper deck plating. This peak displacement reflects the global structural response to the primary hull girder bending moments, specifically under a hogging condition.

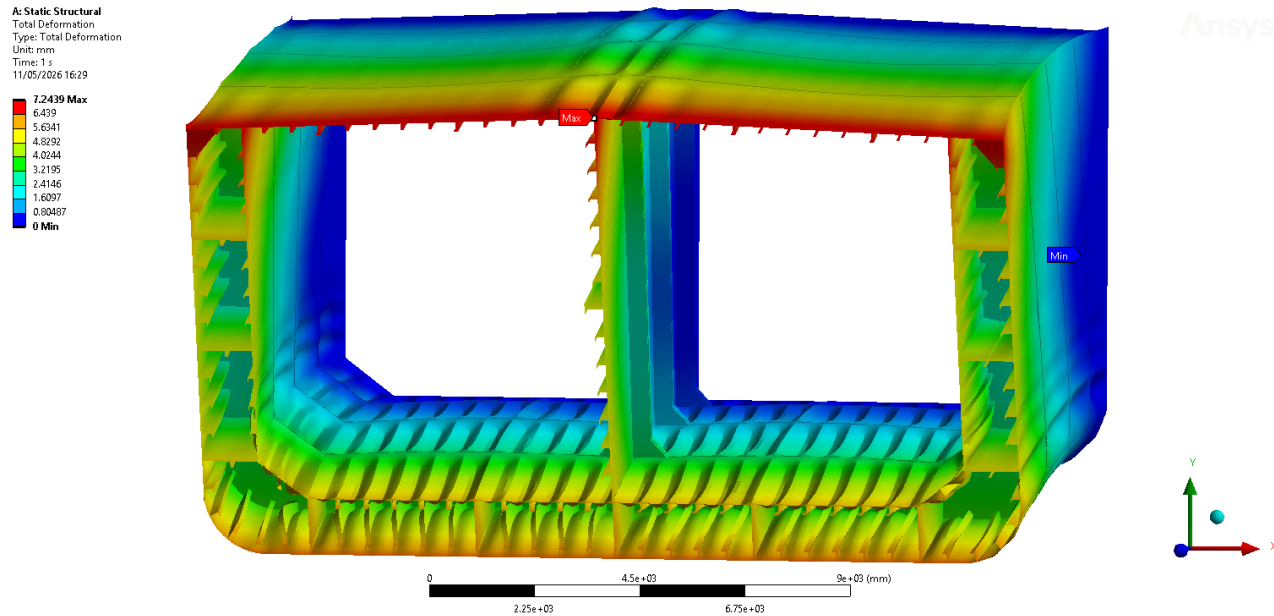


Figure 7-12 Total deformation contour of the baseline midship model. The maximum resultant displacement of 7.31 mm occurs at the deck region, confirming that the initial scantlings possess high structural stiffness prior to the optimisation process.

The vertical deflection observed at the bottom shell remains minimal, indicating that the initial 200 mm web height of the longitudinal stiffeners provides substantial sectional modulus and flexural rigidity. From a regulatory perspective, this maximum displacement is significantly lower than the conventional deflection limit, suggesting that the baseline structure is highly conservative. This surplus in structural stiffness provides a functional "optimisation margin," allowing for the reduction of scantling dimensions, specifically the web height, to enhance robotic accessibility without compromising the overall structural stability or serviceability of the ship block.

7.3.3.3 Baseline Mass and Accessibility Assessment

The total mass of the double bottom structure in its initial state was calculated at 43.68 tonnes. In terms of robotic accessibility, the initial 200 mm web height, while providing robust structural support, restricts the operational "elbow room" for the ABB IRB 1200 manipulator, especially when the robot is mounted on top of the stiffeners. The baseline clearance between the inner bottom plate and the top of the stiffener flange is identified as the primary geometric bottleneck that the subsequent MOGA optimisation aims to resolve.

7.3.4 Response Surface Quality and Goodness of Fit

The reliability of the optimisation results is highly dependent on the accuracy of the Response Surface Methodology (RSM) in representing the structural behaviour of the double bottom block. To evaluate the quality of the constructed surrogate models (G. Guan, Ye, et al., 2025), a Goodness of Fit analysis was performed, as illustrated in Figure 7-13. The predictive accuracy was assessed primarily through the Coefficient of Determination (R^2), which measures how well the regression model fits the actual simulated data points (Myers et al., 2016).

The analysis demonstrated excellent statistical correlation for critical parameters. The Double Bottom Mass exhibited the highest accuracy with an R^2 value of 99%, indicating a near-perfect linear relationship between the scantling variables and the structural weight. The Maximum Equivalent Stress also showed high reliability with an R^2 of 95%, ensuring that the stress constraints within the MOGA framework are based on precise predictions. Meanwhile, the Maximum Total Deformation yielded an R^2 of 80%. Although lower than the other parameters due to the non-linear nature

of global structural stiffness, an R^2 of 0.8 is considered statistically significant and acceptable for complex ship structural optimisation (Guerra et al., 2024). These results confirm that the response surfaces provide a robust foundation for the subsequent genetic algorithm optimisation (Cong et al., 2025).

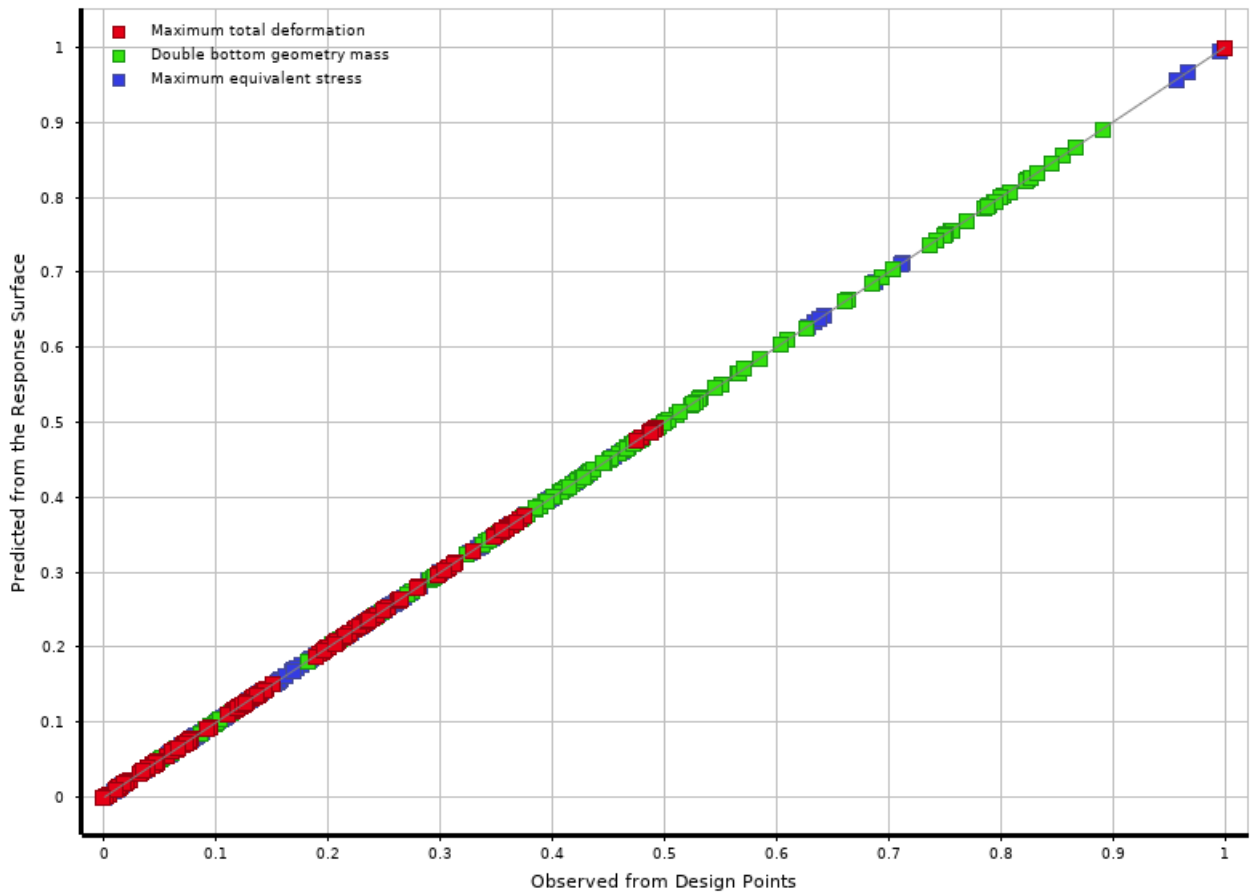


Figure 7-13 Goodness of Fit for the Response Surface Methodology (RSM) comparing predicted versus observed values.

7.3.5 Parameter sensitivity analysis

To identify the most influential design variables on the structural performance of the double bottom block, a local sensitivity analysis was performed based on the Response Surface Methodology. As illustrated in Figure 7-14, the impact of 11

scantling variables was evaluated against three primary output parameters: Total Deformation, Volume Total (Mass), and Equivalent Stress.

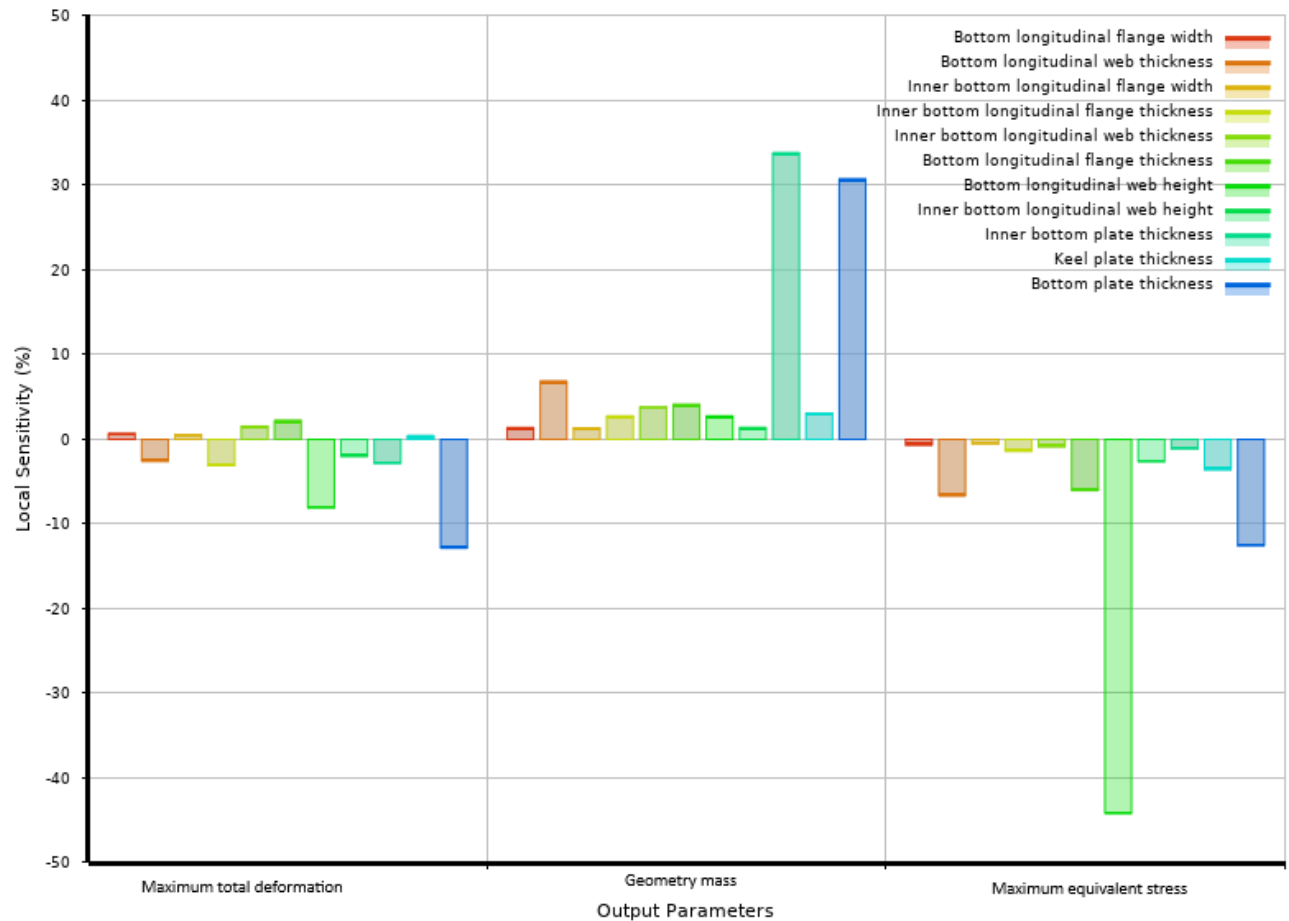


Figure 7-14 Local sensitivity chart displaying the relative impact of scantling design variables on the structural output parameters. The bar chart identifies the primary drivers for mass reduction and stress management, highlighting the critical trade-off between web height reduction and structural stability.

The analysis reveals that Bottom plate thickness and Inner bottom plate thickness are the most dominant factors influencing the Total Volume, contributing significantly to the overall structural mass. Regarding structural integrity, the Equivalent Stress exhibits extreme sensitivity to the Bottom longitudinal web height.

This inverse relationship indicates that even minor reductions in web height to facilitate robotic accessibility lead to a substantial increase in localised stress, necessitating compensatory adjustments in other scantling members. Furthermore, Total Deformation is primarily governed by the plate thicknesses and the longitudinal web heights, confirming that these variables are critical for maintaining the global stiffness of the midship section. These sensitivity results provide a strategic basis for the subsequent multi-objective optimisation, allowing the algorithm to prioritise the most impactful variables to achieve a weight-efficient yet robust design (Montgomery, 2017).

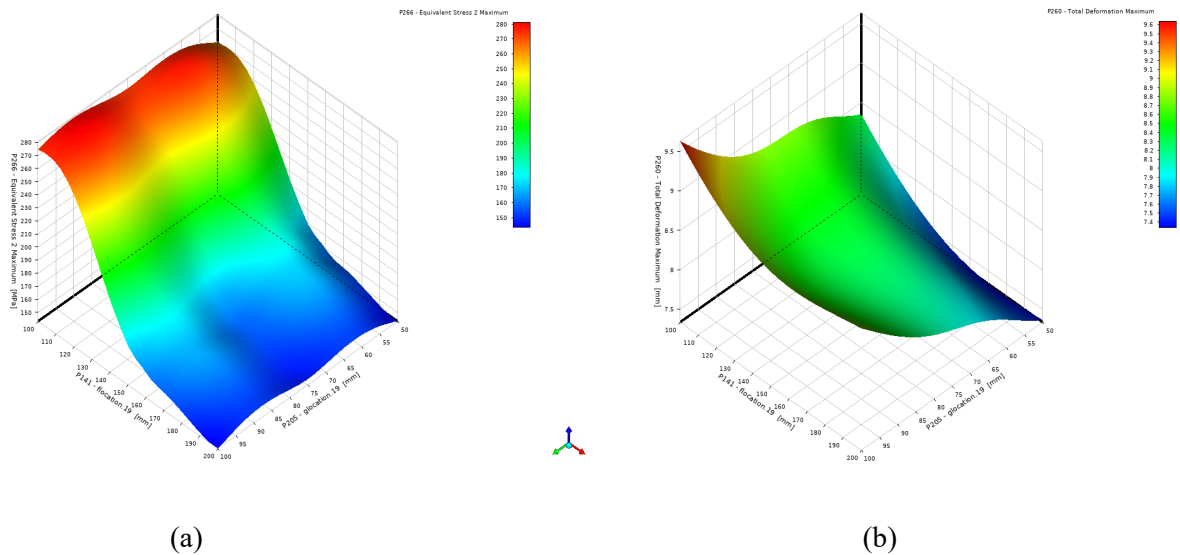


Figure 7-15 3D Response surfaces of the structural behaviour relative to longitudinal web heights: **(a)** Maximum equivalent stress distribution; and **(b)** Maximum total deformation profile.

The sensitivity of the structural responses toward the longitudinal web heights is visualised through 3D response surfaces in Figure 7-15. Figure 7-15a illustrates the maximum equivalent stress distribution as a function of the bottom and inner bottom

longitudinal web heights. It is observed that reducing the web heights to meet robotic accessibility requirements leads to a significant non-linear increase in stress, particularly when both heights approach their lower bounds. However, by maintaining the initial plate thicknesses during this specific sensitivity check, the stress levels are shown to fluctuate between 150 MPa and 280 MPa. This highlights the critical need for compensatory measures, as the reduction in web height directly diminishes the section modulus of the primary stiffening members.

In parallel, Figure 7-15b depicts the total deformation response surface. The chart shows a consistent upward trend in structural deflection as the stiffener heights are decreased. The maximum deformation values range from approximately 7.4 mm to 9.6 mm. This trend underscores the reduction in global stiffness of the double bottom block when the vertical profile of the longitudinals is minimised. The integration of these response surfaces into the MOGA framework allows for a precise trade-off analysis, ensuring that the subsequent weight optimisation, which involves thinning the bottom and inner bottom plates, is balanced by the strategic thickening of the stiffener flanges and webs to keep both stress and deformation within permissible safety limits.

7.3.6 Optimisation Convergence and Computational Performance

The convergence history of the multi-objective optimisation process, specifically for the maximum equivalent stress, is depicted in Figure 7-16. Starting from the initial design state, the Multi-Objective Genetic Algorithm (MOGA) explored a vast design space across approximately 2.9×10^4 design points to identify the global optima. As illustrated in the history chart, the algorithm initially encountered several

design candidates that exceeded the permissible stress threshold of 175 MPa (reaching up to ~187 MPa). Through the enforcement of constraint penalty functions, infeasible scantling combinations were progressively eliminated. As the population evolved, the search space stabilised strictly within the feasible region, culminating in a final Pareto-optimal design that exhibits a maximum equivalent stress of 174.05 MPa, strictly satisfying the 175 MPa regulatory limit.

The occurrence of design points exceeding the 175 MPa threshold during the early and intermediate stages of the iteration reflects the stochastic nature of the Multi-Objective Genetic Algorithm. This behaviour indicates a comprehensive exploration of the design space, where the algorithm evaluates both feasible and infeasible candidates before converging toward the optimal region. The filtering process effectively ensures that only candidates satisfying all structural constraints are included in the final Pareto front.

The high density of design points clustered between 150 MPa and 175 MPa in the later stages of the iteration indicates that the algorithm successfully identified a robust set of Pareto-optimal solutions. This convergence behaviour demonstrates the effectiveness of the MOGA in balancing the conflicting objectives of weight minimisation and structural integrity. The stabilisation of the stress values toward the end of the iteration process confirms that the optimisation has reached a state of convergence (Hanne & Moghaddam, 2025), providing a reliable basis for selecting the final optimised scantlings (Alexakis et al., 2025).

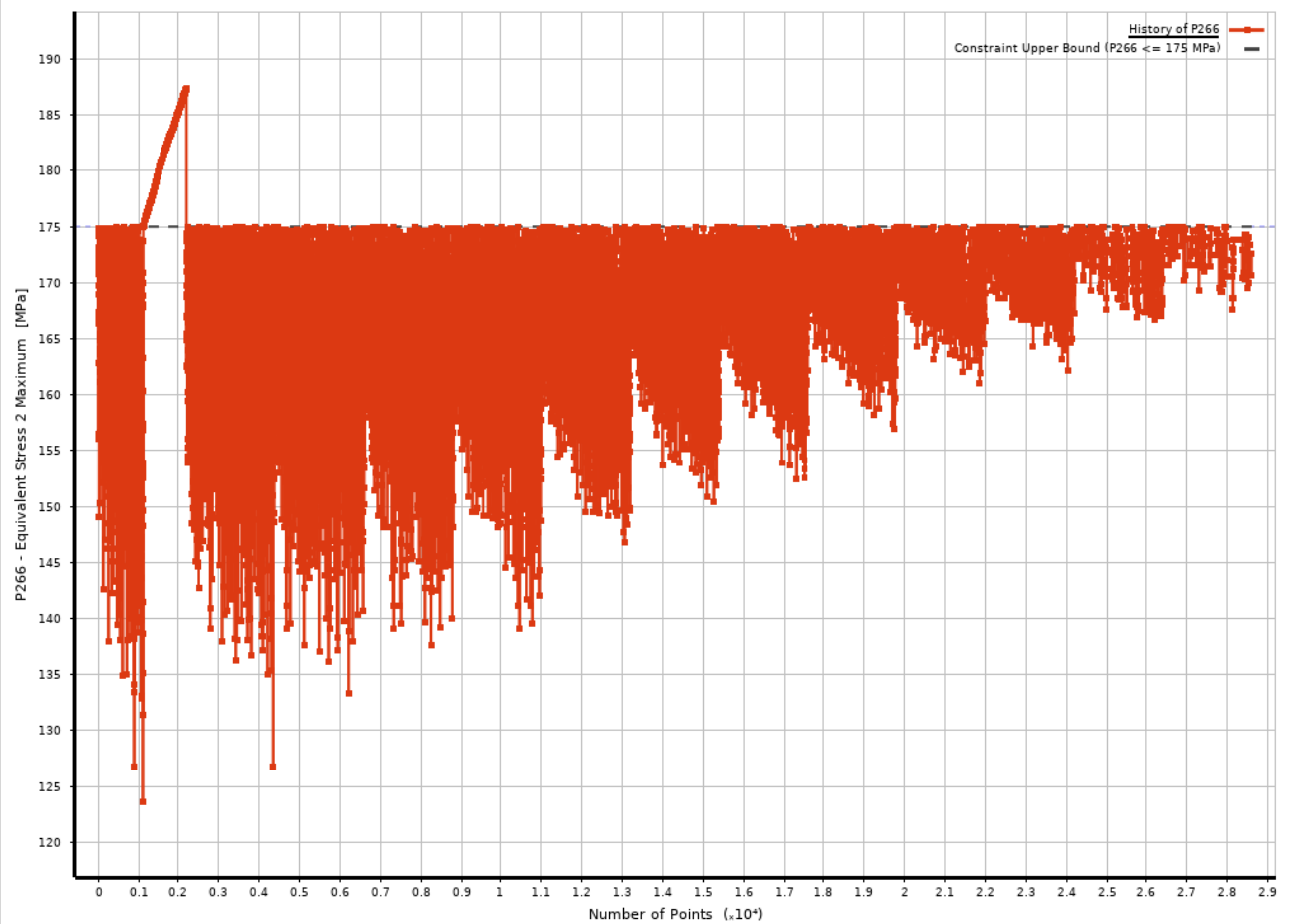


Figure 7-16 Convergence history of the maximum equivalent stress during the multi-objective optimisation process. The chart illustrates the iterative progression toward the feasible design space, with the 175 MPa constraint effectively filtering the Pareto-optimal candidates over 2.9×10^4 design points.

7.3.7 The optimisation results and validation

The final results of the multi-objective optimisation, alongside the initial design parameters and the subsequent FEA verification, are summarised in Table 7-3. The optimisation process significantly redefined the structural scantlings to satisfy the dual objectives of weight reduction and robotic accessibility. Notably, the Inner Bottom Longitudinal Web Height was reduced from 200 mm to 80 mm, and the Bottom

Longitudinal Web Height from 200 mm to 150 mm. These strategic reductions successfully established a vertical clearance of 970 mm [(Note: 1200 - 150 - 80 = 970)], comfortably exceeding the mandatory 950 mm requirement for robotic operations. To compensate for the loss of sectional modulus due to these height reductions, the MOGA algorithm increased specific thickness parameters, such as the bottom longitudinal flange thickness from 10 mm to 16 mm.

Table 7-3 Comparison of structural scantlings and performance metrics between the initial design, MOGA-optimised design, and FEA validation results.

Parameter	Initial Design	Optimum Design	FEA validation
Keel plate thickness	13 mm	12 mm	12 mm
Bottom plate thickness	11 mm	8 mm	8 mm
Inner bottom plate thickness	8 mm	6 mm	6 mm
Bottom longitudinal			
Flange width	100 mm	90 mm	90 mm
Flange thickness	10 mm	16 mm	16 mm
Web height	200 mm	150 mm	150 mm
Web thickness	10 mm	12 mm	12 mm
Section Modulus	214590 mm ³	214022 mm ³	214022 mm ³
Inner Bottom longitudinal			
Flange width	100 mm	70 mm	70 mm
Flange thickness	10 mm	14 mm	14 mm
Web height	200 mm	80 mm	80 mm
Web thickness	10 mm	8 mm	8 mm
Section Modulus	224490 mm ³	109540 mm ³	109540 mm ³
Maximum Stress	145.46 MPa	174.90	174.05
Maximum Deformation	7.24 mm	9.48 mm	9.10 mm
Double bottom mass	43678.86 Kg	35747.57 Kg	35752.09 kg

The structural performance of the optimum design remained well within the safety limits. The maximum equivalent stress increased from 145.46 MPa to 174.90 MPa, aligning closely with the 175 MPa constraint. To ensure the reliability of the surrogate-based optimisation, the optimised configuration was re-simulated in the FEA environment. The validation results show a remarkably high degree of correlation; the maximum stress recorded in FEA was 174.05 MPa (a 0.48% deviation), and the total mass was 35,752.09 kg (a negligible 0.012% deviation from the predicted 35,747.57 kg). Furthermore, the maximum deformation of 9.10 mm remains safely below the 12 mm limit. These findings confirm that the optimisation framework successfully achieved an 18.15% mass reduction without compromising the structural integrity or serviceability of the double bottom block.

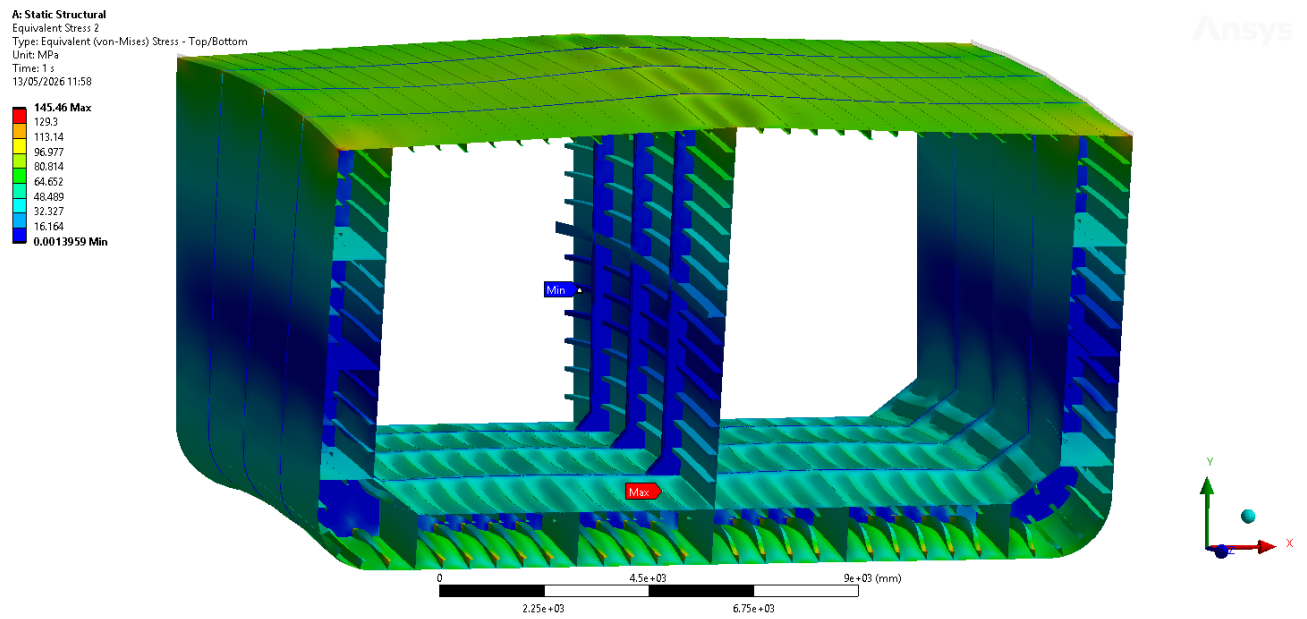
To address the regulatory requirements and ensure that the finite element validation is supported by analytical compliance, the standard section moduli (Z_{req}) of the longitudinal stiffeners were calculated in accordance with class rule principles. The lateral hydrostatic and cargo pressures (P) were determined based on an operational ship draft of $T = 6.7$ m for the bottom plating, yielding an external pressure of $P_1 = 0.0673$ MPa, and a cargo density of $\rho_{\text{cargo}} = 745$ kg/m³ for the inner bottom plating, resulting in a pressure of $P_2 = 0.0426$ MPa. Using these operational boundary parameters combined with an allowable class stress limit of $\sigma_{\text{allow}} = 175$ MPa over an unsupported frame span of $\ell = 3000$ mm and spacing $S = 600$ mm, the minimum required section moduli were evaluated as $Z_{\text{req1}} = 173.18$ cm³ for the bottom longitudinals and $Z_{\text{req2}} = 109.53$ cm³ for the inner bottom longitudinals. As detailed in Table 3, the actual section moduli of the MOGA-optimised design, evaluated with

an effective attached plating breadth of $b_{\text{eff}} = 600$ mm, achieve $Z_{\text{act1}} = 214.02 \text{ cm}^3$ and $Z_{\text{act2}} = 109.54 \text{ cm}^3$ respectively. Both values successfully satisfy the condition $Z_{\text{act}} \geq Z_{\text{req}}$, confirming that the optimisation results meet mandatory regulatory standards prior to FEA verification.

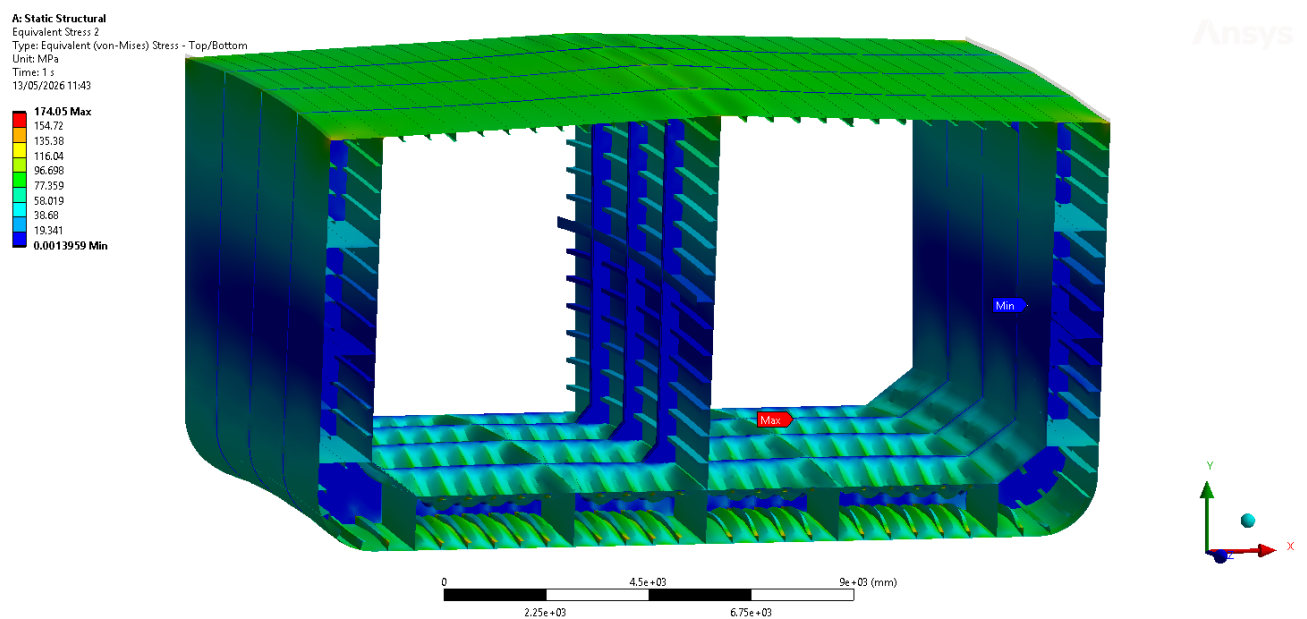
7.3.8 Comparative Analysis of Equivalent Stress Distribution

The structural response in terms of Von-Mises equivalent stress was evaluated to ensure that the weight reduction did not compromise the structural integrity of the midship section. As shown in Figure 7-17(a) the initial design exhibited a maximum equivalent stress of 145.46 MPa, which is significantly lower than the permissible stress limit, indicating an over-designed structure with excessive material redundancy. Following the multi-objective optimisation, the stress distribution was redistributed more efficiently across the structural members. In the optimised configuration shown in Figure 7-17(b), the maximum equivalent stress increased to 174.05 MPa.

This increase in stress is a direct consequence of the aggressive scantling reduction, particularly the thinning of the bottom and inner bottom plates and the reduction of longitudinal web heights. Despite the 19.65% increase in peak stress compared to the initial state, the optimised value of 174.05 MPa remains strictly below the designated design constraint of 175 MPa. The contour plots reveal that the high-stress regions remain concentrated at the longitudinal members of the bottom structure, where the global bending moments are most prominent. These results demonstrate that the optimisation framework successfully pushed the structural limits to achieve maximum weight efficiency while maintaining a safety factor within the allowable limits of the classification society standards.



(a)



b)

Figure 7-17 Equivalent (Von-Mises) stress distribution for a) the initial design state and b) the optimised design.

7.3.9 Comparative Analysis of Total Deformation

The structural stiffness of the midship section was evaluated by comparing the total deformation profiles before and after the optimisation process. As illustrated in Figure 7-18(a), the initial design configuration exhibited a maximum total deformation of 7.31 mm, primarily localised at the centre of the deck plating. Following the multi-objective optimisation, the maximum deformation increased to 9.10 mm, as shown in Figure 7-18(b). This 24.5% increase in displacement is a direct consequence of the aggressive weight reduction and the lowering of longitudinal stiffener web heights to accommodate robotic accessibility.

Despite the increase, the optimised deformation value of 9.10 mm remains significantly below the serviceability limit of 12 mm typically mandated by classification societies to prevent functional interference and secondary stress effects (Hughes et al., 2010) (Lloyd's Register (LR), 2024). The contour distribution remains consistent between both models, indicating that while the structural redundancy has been reduced to achieve an 18.15% mass saving, the global stiffness characteristics of the double bottom block are preserved. This confirms that the optimised scantlings provide a balanced solution between manufacturing flexibility and structural serviceability.

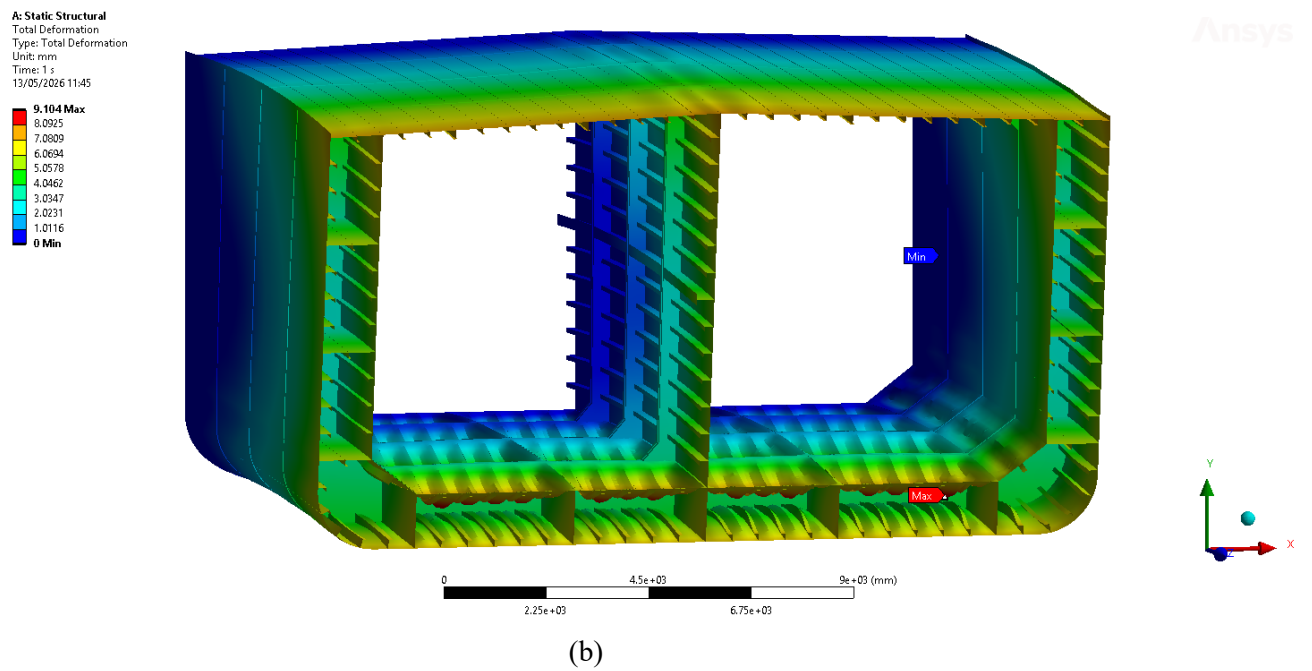
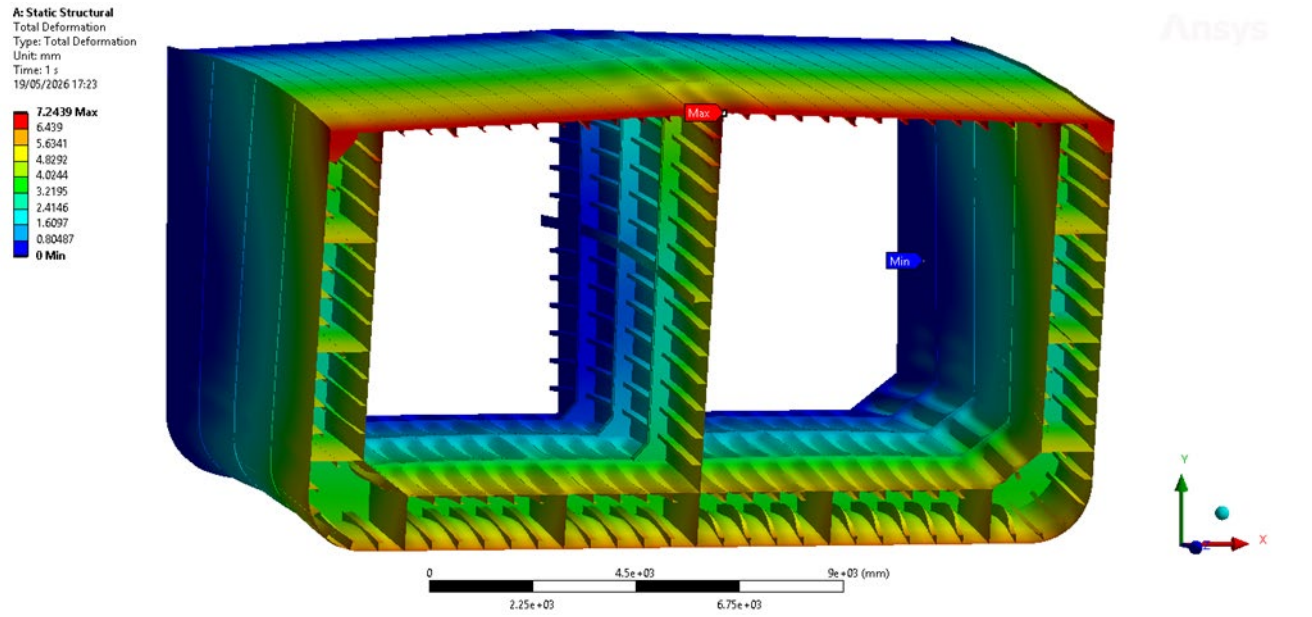
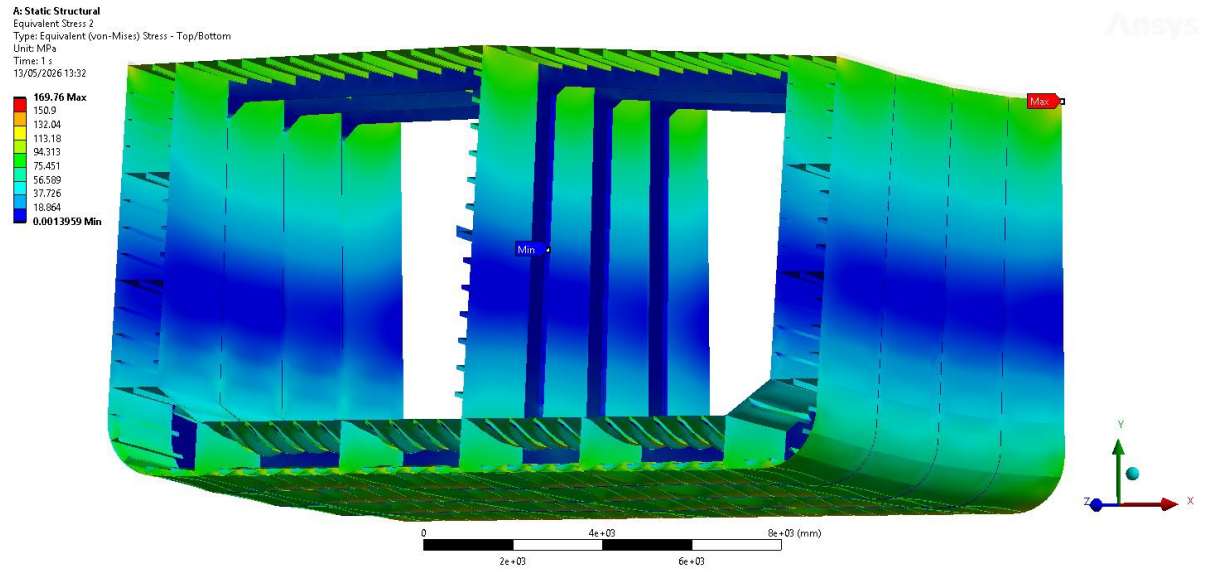


Figure 7-18 Total deformation contour plots of the midship section: (a) Initial design showing a maximum displacement of 7.24 mm; and (b) Optimised design demonstrating a maximum displacement of 9.10 mm, maintained within the allowable serviceability limits.

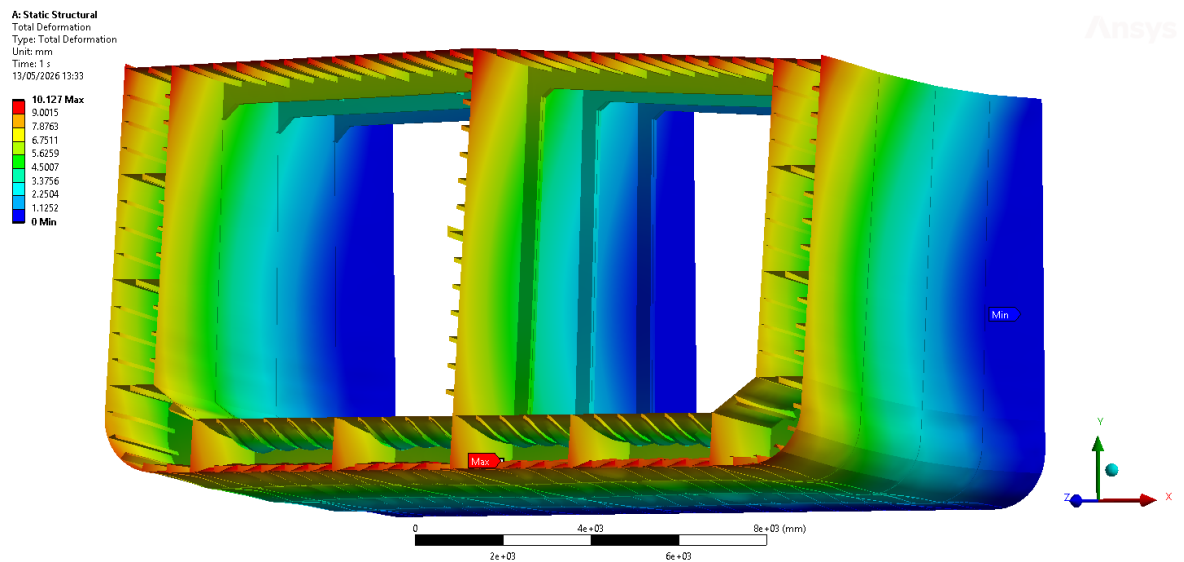
7.3.10 Structural Integrity Validation under Sagging Moment

To further validate the reliability of the optimised geometry, a global longitudinal strength analysis was conducted under a critical sagging condition. A vertical bending moment of -321,188.6 kNm was applied to the midship section. As illustrated in Figure 7-19a, the maximum equivalent stress recorded under this load is 169.76 MPa. This value is well within the permissible limits, confirming that the reduction in scantlings does not lead to structural failure when subjected to maximum longitudinal bending. The stress distribution shows that the most intensive loads are effectively carried by the continuous longitudinal members of the double bottom and deck structures.

In terms of stiffness, the total deformation under the sagging moment is shown in Figure 7-19b. The maximum deformation is recorded at 10.127 mm, located at the bottom shell where the compression from the sagging moment is most significant. This deflection remains within the acceptable serviceability range, ensuring that the structural integrity and functional requirements of the confined spaces are maintained even under extreme operational loads. This evaluation confirms that the MOGA-optimised design strikes an excellent balance between aggressive weight reduction and robust longitudinal strength, adhering to the safety standards required for ship structures (Hughes et al., 2010) (Lloyd's Register (LR), 2024).



(a)



(b)

Figure 7-19 Structural response of the optimised double bottom block under a sagging moment of -321,188.6 kNm: (a) Equivalent (Von-Mises) stress distribution showing a peak of 169.76 MPa; and (b) Total deformation contour with a maximum displacement of 10.127 mm.

7.3.11 Buckling Strength Verification under Hogging Condition

The structural stability of the optimised double bottom block was further evaluated through an eigenvalue buckling analysis under the most demanding load combination, specifically the hogging moment and concurrent hydrostatic pressures. In a hogging condition, the ship's hull experiences a vertical bending moment that induces significant compressive stresses in the double bottom structure and tensile stresses in the deck region. This compressive state makes the bottom longitudinal members highly susceptible to elastic instability.

To rigorously ensure the structural stability of the optimised double bottom, an extended eigenvalue buckling analysis was conducted, evaluating the first 50 modes under a combined hogging moment and hydrostatic pressure. The results, consolidated in Figure 7-20, demonstrate a hierarchical failure progression where all positive load multipliers remain above the safety threshold. The most critical failure state is identified in the primary supporting members, specifically the port and starboard side girders, with minimum load multipliers of 1.1306 and 1.1309, respectively. These initial modes indicate that the side girders are the most sensitive components to the global longitudinal compression induced by the hogging moment.

Furthermore, higher-order modes from the 50-mode sequence were analysed to evaluate local plate stability. As shown in the lower panels of Figure 7-20, subsequent buckling modes transition to the inner bottom plate panels. Despite the reduction in inner bottom plate thickness as part of the weight optimisation strategy, these local modes yield acceptable load multipliers (e.g., mode 46 at $\lambda = 1.171$ and mode 50 at

$\lambda = 1.181$), confirming that the plate panels possess sufficient stiffness to resist elastic buckling.

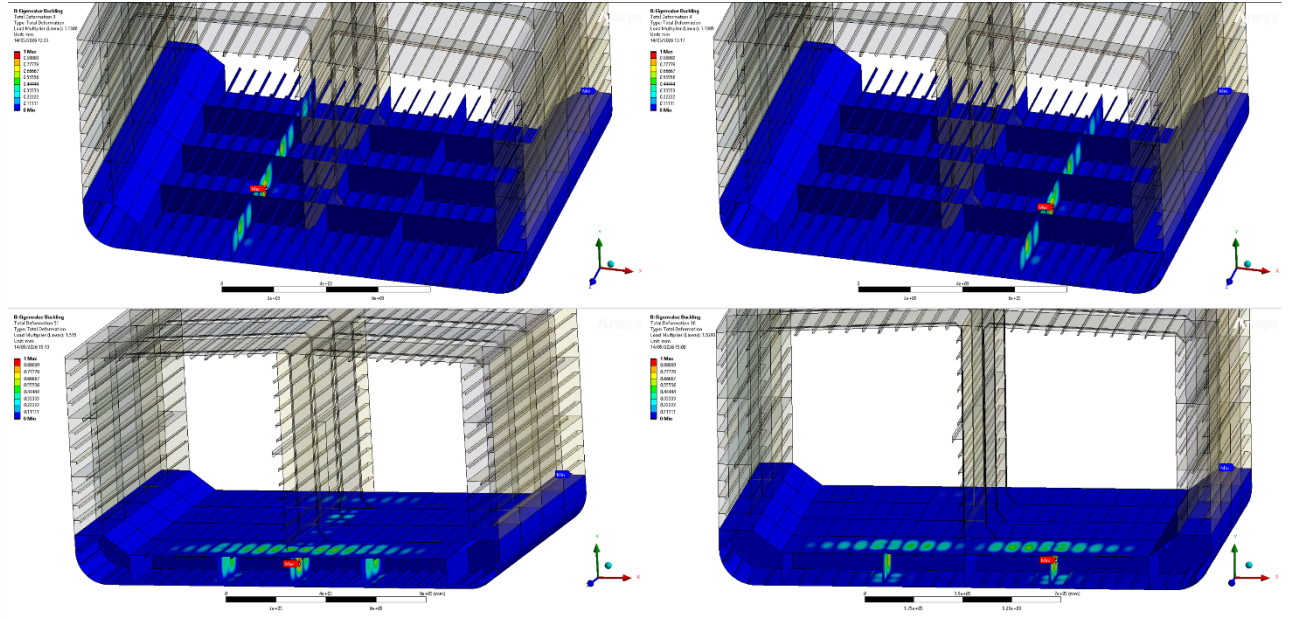


Figure 7-20 Multi-mode eigenvalue buckling results of the optimised design: The upper panels show the primary buckling modes occurring at the side girders ($\lambda \approx 1.13$); the lower panels illustrate the local buckling modes occurring at the inner bottom plate panels ($\lambda > 1.17$). All modes demonstrate a load multiplier > 1.0 , validating structural stability.

According to the IACS Common Structural Rules (CSR) and Lloyd's Register (LR) ShipRight procedures (Lloyd's Register (LR), 2025), a design is considered safe if the buckling utilisation factor remains below 1.0, or conversely, if the linear load multiplier exceeds the unity threshold ($\lambda > 1.0$). With a minimum multiplier of 1.1306, the optimised structure provides a 13.06% safety margin against elastic buckling. The consistent safety margin across both primary and secondary structural members proves that the optimised scantlings comply with the regulations. This result

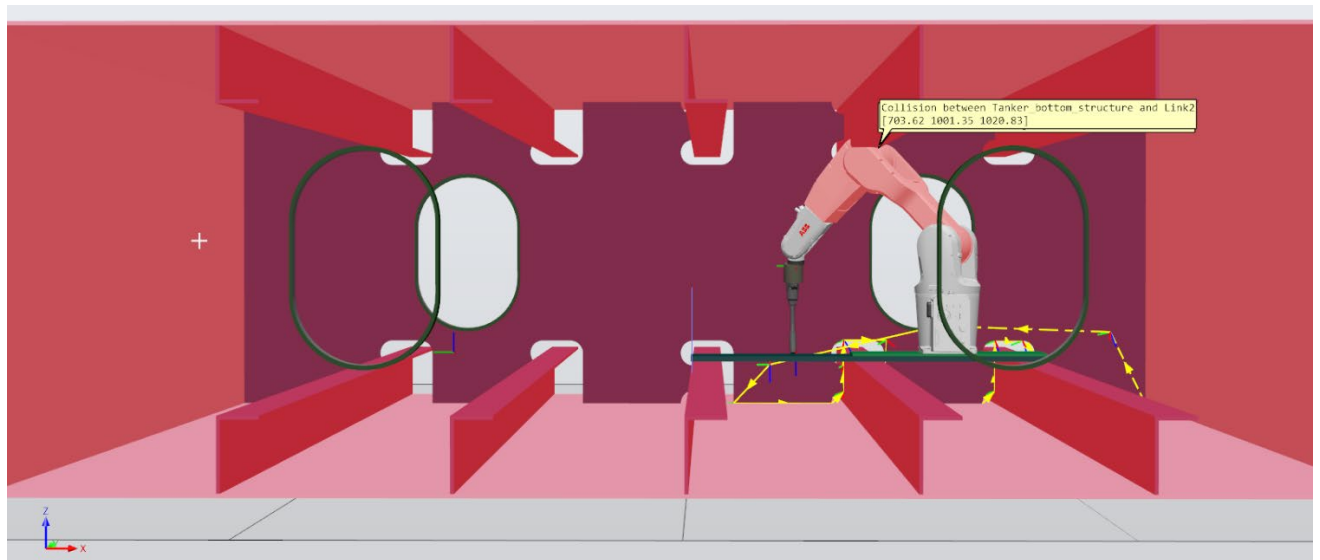
confirms that the reduction in web heights and plate thicknesses, compensated by increased flange scantlings, successfully maintains structural stability while facilitating robotic access.

7.3.12 Robotic Accessibility and Welding Path Verification

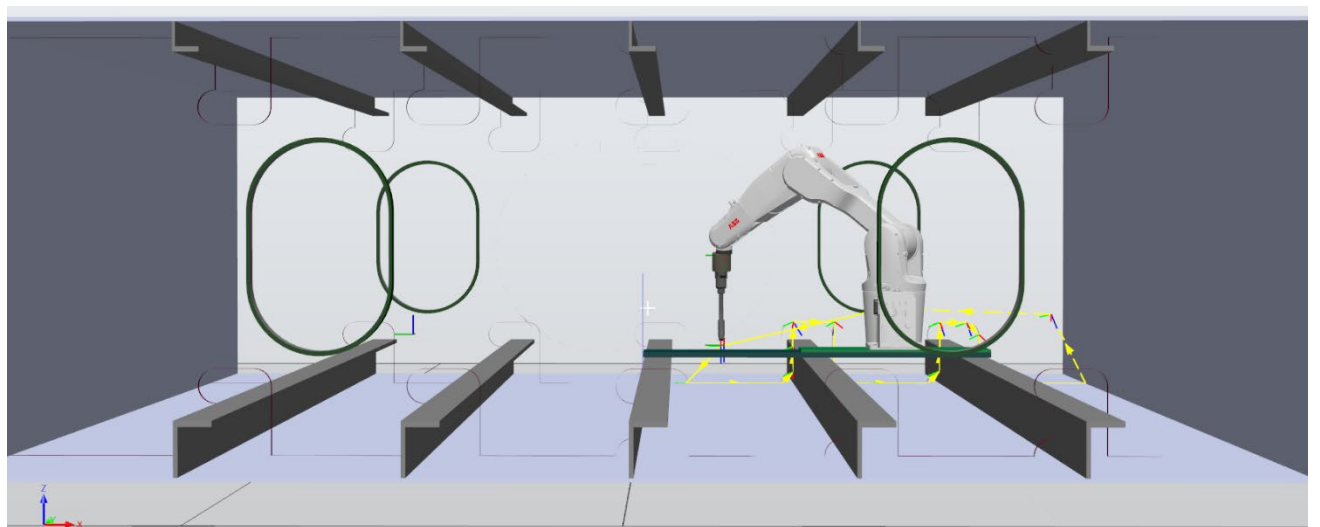
The practical feasibility of the proposed structural modifications was validated through a comparative robotic simulation in the double bottom confined space. Figure 7-21a illustrates the Initial Design, where the original stiffener web heights (200 mm) create a highly restrictive environment for the robotic manipulator. In this configuration, the limited vertical clearance significantly constrains the robot's range of motion, leading to the previously identified collision risks during the transition and welding phases. The tight spatial boundaries force the robot arm into suboptimal postures, which not only increases the likelihood of mechanical interference with the structural members but also limits the effective welding coverage.

In contrast, the Optimised Design shown in Figure 7-21b demonstrates a marked improvement in operational clearance. By reducing the bottom and inner bottom longitudinal web heights to 150 mm and 80 mm respectively, the vertical working envelope was expanded to 970 mm. This enhanced clearance allows the robot to execute the programmed welding paths with greater fluidity and safety. The simulation confirms that the optimised geometry provides sufficient "swept volume" for the robot arm to navigate from its home position to the weld joints without any collision recorded. This verification proves that the structural optimisation not only achieves mass efficiency but also successfully transforms a previously inaccessible confined

space into a viable environment for automated robotic manufacturing (Wahidi et al., 2024) (Saidi et al., 2016).



(a)



(b)

Figure 7-21 Comparative robotic welding simulation in ABB RobotStudio: (a) Initial design with 200 mm stiffener heights showing restricted manipulator access; and (b) Optimised design with reduced web heights, providing enhanced clearance for collision-free robotic operations.

7.3.13 Dynamic Performance and Manufacturing Feasibility Validation

The manufacturing feasibility of the optimised double bottom structure was further validated through a comprehensive robotic welding simulation, as analysed in Figure 7-22. The recorded analogue signals provide deep insights into the robot's operational stability within the modified design space. The Total Motor Energy curve exhibits a smooth, linear progression, while the Total Motor Power remains stable with only minor fluctuations corresponding to the specific welding joint transitions. Most critically, the Digital Signals log confirms a total absence of collision events throughout the 03:15 minute simulation cycle. The lack of any "Collision" signal (indicated by a flat line in the digital signal section) proves that the increased vertical clearance provided by the optimised scantlings successfully accommodates the swept volume of the robotic manipulator. Furthermore, the stable joint kinematic profiles (J1–J6) and Cartesian coordinates (X, Y, Z) indicate that the welding path was executed without reaching singularity points or near-limit joint constraints. This data empirically demonstrates that the proposed structural optimisation effectively bridges the gap between weight efficiency and automated manufacturing accessibility in ship confined spaces.

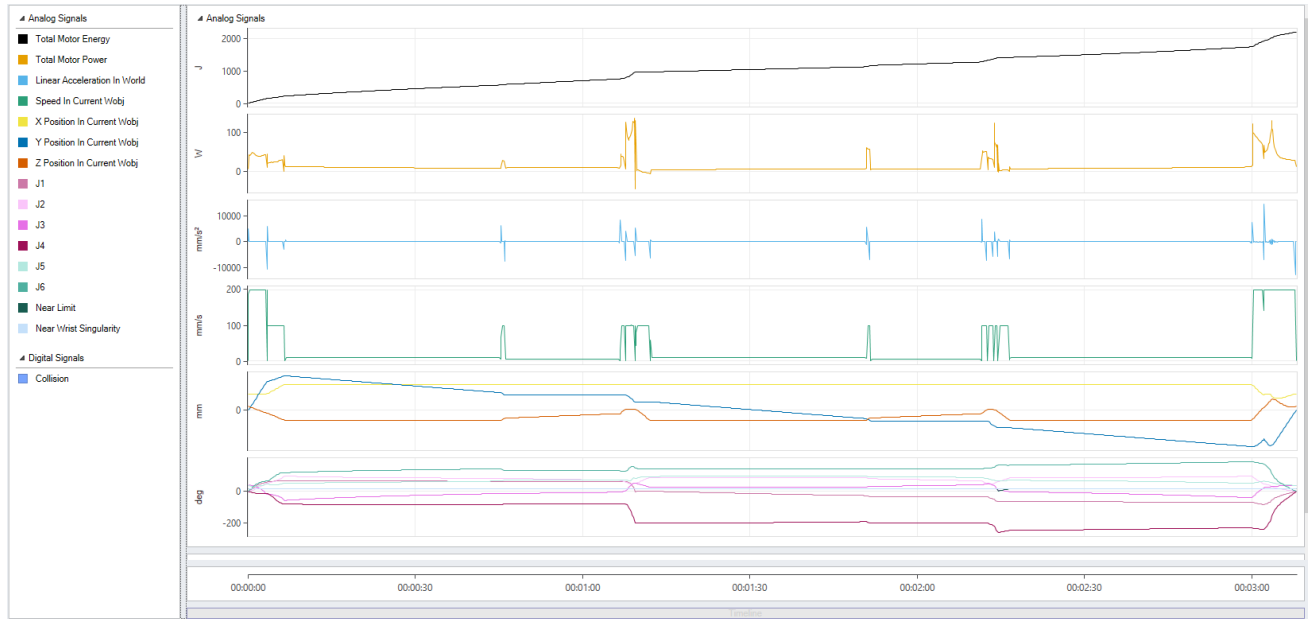


Figure 7-22 Dynamic signal analysis of the robotic welding process on the optimised geometry. The chart tracks energy consumption, motor power, and kinematic joint positions, confirming a collision-free operation and high kinematic stability within the enhanced double bottom working envelope.

7.4 Discussion

7.4.1 Geometric Trade-offs and Structural Efficiency

The primary challenge in optimising the double bottom structure lies in the conflicting nature of weight reduction and robotic accessibility. The initial design, while robust, was characterised by significant material redundancy, as evidenced by a maximum equivalent stress of only 145.46 MPa. The transition to the optimised design pushed the structural utilisation closer to the permissible limit of 175 MPa, achieving a maximum stress of 174.05 MPa.

This shift represents a more efficient use of material, where the structural capacity is fully leveraged to reduce the total mass by 18.15% (from 43,678.86 kg to

35,752.09 kg). The sensitivity analysis and 3D response surfaces further clarified that the bottom longitudinal web height (h_{wl}) is the most critical parameter influencing structural integrity. By strategically increasing the flange thickness of the bottom longitudinals from 10 mm to 16 mm, the MOGA framework successfully compensated for the reduction in web height, maintaining the required sectional modulus while freeing up essential vertical space.

7.4.2 Impact of Structural Optimisation on Robotic Accessibility

The core contribution of this research is the integration of manufacturing constraints into the structural design phase. The initial simulation in ABB RobotStudio clearly demonstrated that a standard structural configuration (200 mm web heights) results in mechanical interference during the approach and retraction phases of the welding cycle. These collisions, identified through digital signal logs, confirm that traditional "shipbuilding-first" design approaches are a major bottleneck for automation.

By establishing a minimum clearance constraint of 950 mm within the optimisation framework, the resulting geometry provided a final working envelope of 970 mm. The verification simulation on the optimised design showed a zero-collision status, with stable motor power and smooth kinematic transitions. This indicates that structural optimisation can proactively solve collision problems that are otherwise difficult to manage through robotic path planning alone in such highly confined spaces.

7.4.3 Comparative Analysis with Prior Optimisation Approaches

The primary novelty of this research lies in its holistic approach to structural optimisation, which integrates mass reduction with manufacturing efficiency and

operational safety as illustrated in Table 7-4. Unlike conventional optimisation studies that focus solely on weight minimisation (G. Guan & Yang, 2018), this framework enforces a constant number of stiffeners while strategically reducing web heights to expand the working envelope for automated production systems. This geometric modification is critical for enabling robotic welding within the double bottom's confined spaces, thereby significantly reducing the need for manual welding during the join assembly phase which is a process traditionally associated with high safety risks and lower efficiency.

Table 7-4 Comparison of optimisation strategies and manufacturing implications.

Parameter	Reviewed Studies	Prior Structural Baseline (Wahidi et al., 2025)	Proposed Research Framework (Current Work)
Primary Objective	Structural weight minimisation	Geometry mass and welding volume minimisation	Structural weight reduction and robotic accessibility
Stiffener Quantity	Increased (to compensate for reduced plate thickness)	Constant (same as initial model)	Constant (maintained to minimise welding length)
Stiffener Web Height	Standard / Variable	Minimised (to reduce welding volume)	Minimised (strategically reduced to maximise vertical working clearance)
Production Impact	Increased welding length and material handling	Reduced welding volume and simplified assembly	Reduced welding volume and enabled automated fabrication
Manufacturing Method	Primarily manual / Conventional	Primarily manual / Conventional	Automated (Robotic welding)
Safety Aspect	Standard regulatory compliance	Reduced human exposure in confined spaces	Enhanced safety (minimised human presence in confined spaces)
Cost Considerations	Material cost only	Material and fabrication costs	Material and automated production costs

In contrast to previously published works (Putra et al., 2019), which achieved weight reduction at the expense of increasing the total number of stiffeners, our approach prioritises production cost-effectiveness. Increasing stiffener count, as seen in traditional optimisation, leads to a direct escalation in welding length, material handling complexity, and overall production costs (Lin & Shaw, 2017). By maintaining a constant stiffener count and focusing on compensatory scantling thickening (e.g., increasing flange thickness), the proposed method ensures that structural integrity is preserved while simultaneously optimising the ship block for modern automated manufacturing paradigms.

To justify the proposed methodology, the framework is contextualised against both conventional structural optimisation approaches (e.g., Putra et al., 2019) and the authors' prior baseline framework (Wahidi et al., 2025). As shown in Table 7-4, conventional optimisation studies frequently achieve weight reduction by increasing the total stiffener count. However, this stiffener proliferation directly escalates total welding volume, material handling complexity, and overall manufacturing costs, while drastically restricting workspace within confined double bottom blocks. In our prior work (Wahidi et al., 2025), this limitation was resolved by enforcing a constant stiffener count, utilising commercially available steel plate scantlings under Lloyd's Register rules, and reducing web plate heights to minimise total production costs.

Building upon the foundation of Wahidi et al. (2025), the current study advances the methodology by integrating explicit robotic spatial constraints ($C_{\text{robot}} \geq 950 \text{ mm}$) into the MOGA optimisation loop. By directly modelling the dynamic kinematic envelope of an ABB IRB 1200 manipulator within the restricted 1200 mm

compartment, the proposed design achieves an optimal balance: an 18.15% mass reduction combined with a verified zero-collision status for automated welding, without increasing stiffener count or production complexity.

7.4.4 Compliance with Marine Structural Standards

Despite the aggressive scantling reduction, the optimised structure remains fully compliant with the Lloyd's Register (LR) (2024) and IACS Common Structural Rules (CSR) (2024). The evaluation under global sagging moments resulted in a peak stress of 169.76 MPa and a total deformation of 10.127 mm, both of which are within the safety and serviceability envelopes. Furthermore, a comprehensive buckling verification across 50 modes confirms that the structure maintains elastic stability under critical hogging conditions. With a minimum load multiplier of 1.1306, the primary members exhibit a robust safety margin against global buckling, while higher-order modes confirm that the optimised plate panels are resistant to local instability. This ensures that the proposed 'robotic-friendly' design is not only manufacturable but also sea-worthy and capable of withstanding extreme operational loads throughout its service life.

7.4.5 Research Limitations

Despite the significant advancements in weight reduction and manufacturing accessibility, several limitations must be acknowledged. First, the structural stability was evaluated using linear Eigenvalue Buckling Analysis, which, although sufficient for identifying critical load multipliers, does not account for non-linear geometric effects or post-buckling behaviour that could be captured through a more complex ultimate strength analysis. Second, while the robotic welding verification in ABB

RobotStudio confirmed a zero-collision status, the simulation environment does not fully replicate shipyard dynamic variables, such as thermal distortion during welding or minor assembly misalignments. Lastly, the optimisation was focused on the midship double bottom block; therefore, the derived scantling configurations may require further adjustment for extreme fore or aft sections where structural curvatures and load distributions vary significantly.

Chapter 8. Conclusion

8.1 Summary of the Study Findings

This doctoral thesis has successfully established a comprehensive, multi-disciplinary framework for integrating robotic welding constraints into the structural optimisation of ship structures, effectively bridging the historical gap between structural naval architecture and automated manufacturing capabilities. By treating robotic kinematic boundaries as active design constraints rather than post-design considerations, this research provides a scalable solution to the long-standing challenges of automating welding processes within highly restricted internal compartments, specifically ship double-bottom blocks with extreme 1200 mm height constraints.

The fundamental conclusions derived from the five interconnected phases of this research are summarised as follows:

1. This systematic literature review maps the state of the art and identifies critical research gaps in the deployment of robotic welding within marine structures and production processes. The findings reveal that while industrial automation has advanced significantly, future research must shift toward sustainability by developing energy-efficient welding processes that integrate renewable energy sources, waste heat recovery systems, and proactive emissions management to promote greener maritime practices. Furthermore, given the rapid adoption of high-strength alloys and advanced materials in shipbuilding, a studies must investigate specific metallurgic welding challenges and optimisation strategies to ensure seamless compatibility with robotic systems. The review highlights that the

integration of advanced sensors, artificial intelligence, and machine learning is poised to drive the field forward by enabling real-time process optimisation and automated defect detection. To justify these technical transitions, there is a pressing need for sector-specific cost-benefit analyses and economic models tailored to the marine industry. Ultimately, this review concludes that shifting the paradigm toward structural optimisation that proactively considers automated, robot-based ship production represents the true state of the art, serving as a critical foundation for next-generation naval architecture.

2. The empirical evaluation of the ship's block panel assembly process establishes that robotic welding achieves a 3.85-fold increase in processing speed compared to conventional manual methods, drastically compressing the manufacturing timeline required to complete intricate double-bottom structural blocks. Furthermore, resource allocation analysis reveals a highly efficient consumption ratio of 1:2.75 for electricity and man-hours when transitioning from conventional to automated welding. By quantifying these operational metrics, the economic analysis mathematically demonstrates that despite the initial capital investment, robotic welding yields substantial long-term cost savings through the concurrent reduction of labour expenditures and optimisation of energy overheads, thereby providing a robust financial and operational justification for automated production lines in modern shipyards.
3. The structural optimisation framework designed to concurrently minimise structural weight and the extent of welding operations in confined shipbuilding spaces enhance occupational safety and reducing production costs. While

conventional optimisation trends achieve lighter hulls by increasing stiffener density and reducing plate thickness, they inadvertently escalate manufacturing complexity, fabrication time, and labour expenses. The proposed methodology integrates a Multi-Objective Genetic Algorithm (MOGA) with Response Surface Methodology (RSM) alongside a classification of strict constraint rules resolve this conflict. By minimising both geometric mass and web plate heights, the latter directly correlating to localised weld lengths, while rigorously adhering to classification society rules, the framework successfully maps the Pareto-optimal design space. The resulting configurations demonstrate that stiffened ship panels can be engineered to be structurally lighter while significantly shortening internal welding paths, providing a scalable strategy for cost-efficient and safer automated production in restricted maritime environments.

4. This research validates a Virtual Prototyping Framework (VPF) that successfully isolates the kinematic dexterity scores of a 6-axis industrial manipulator operating within a 1.2-meter confined double-bottom block across floor, elevated, and inverted mounting typologies. The Digital Twin Prototype (DTP) approach demonstrates that the Elevated (On-Stiffener) configuration is the most commercially viable solution for continuous production; while floor mounting provides excellent stability, its required manual repositioning incurs inefficient cycle times, and inverted configurations trigger high collision risks and joint singularity issues due to compressed vertical clearances. Crucially, the kinematic analysis identifies Axis 3 (elbow) collision risks with the ceiling and joint limit saturation as the primary automation bottlenecks, confirming that standard ship

geometries are natively restrictive for industrial manipulators. This research highlights a critical paradigm shift required in modern maritime engineering: transitioning from manual-centric layouts to a robust 'Design for Automation' (DfA) framework. The restricted accessibility of lower corner fillet welds and the kinematic collisions between the manipulator and structural components during elevated-position welding stem from severe spatial constraints that can only be resolved through targeted structural modifications. Ultimately, the successful realisation of Shipbuilding 4.0 depends on a co-design synergy between robotic path planning and ship structural architecture.

5. This research validates the integrated Multi-Objective Structural Optimisation (MOSO) framework applied to a ship's double-bottom block, successfully bridging the gap between structural efficiency and automated manufacturability. The framework achieved an 18.15% reduction in structural mass while maintaining a constant stiffener count to minimise total weld length, material handling complexity, and production overheads. Functionally, the strategic optimisation of longitudinal web heights expanded the vertical working envelope required for collision-free robotic operations inside the compressed 1200 mm compartments, as confirmed by high-fidelity ABB RobotStudio simulations. Regarding structural integrity, the design strictly complies with IACS CSR and Lloyd's Register (LR) standards; it keeps the maximum equivalent stress at 174.05 MPa (below the 175 MPa limit) via compensatory thickening of the webs and flanges, while the eigenvalue buckling analysis under combined hogging moments and hydrostatic pressures guarantees resilience with a safe minimum load multiplier of 1.1306.

Demonstrating exceptional numerical precision with an error margin below 0.5%, this research conclusively proves that embedding robotic operational limits into early-stage Design for Manufacturing and Assembly principles is a highly reliable and optimal strategy for advancing automation, productivity, and structural safety in modern shipbuilding.

In summary, this thesis proves that structural efficiency (weight reduction) and advanced manufacturing automation (robotic accessibility) are mutually compatible parameters that can be concurrently resolved within a multi-objective optimisation framework. The developed framework provides naval architects and ship designers with the necessary mathematical and computational tools to proactively engineer next-generation maritime structures that are inherently optimised for automated production.

8.2 Significance of the Contributions

This doctoral research yields five distinct contributions that advance the state of the art in naval architecture, evolutionary structural optimisation, and maritime manufacturing automation:

1. This research shifts the traditional ship design paradigm from a manual-centric model to a proactive "Design for Automation" (DFA) framework. By mapping the global industrial gaps, the study establishes that structural optimisation must be intrinsically connected to manufacturing realities. It provides the theoretical foundation for incorporating emerging Industry 4.0 pillars, such as artificial intelligence, real-time defect detection, metallurgical compatibility for high-strength alloys, and energy-efficient, green manufacturing metrics, directly into the early-stage synthesis of next-generation maritime vessels.

2. The study provides a rigorous mathematical and financial baseline that proves the viability of shipyard automation over legacy manual labour. By quantifying a 3.85-fold increase in processing speed alongside a highly efficient 1:2.75 consumption ratio for electricity and man-hours, this research removes commercial ambiguity. It offers global shipyards a robust economic model of automated robotic lines through verified, long-term labour and operational energy overhead savings.
3. This work resolves a long-standing conflict in structural engineering where "weight-centric" designs inadvertently expand weld lengths, thereby inflating manufacturing labour and cycle times. By integrating a Multi-Objective Genetic Algorithm (MOGA) with Response Surface Methodology (RSM) under strict constraint rules, this research successfully maps a unique Pareto-optimal design space. The methodological innovation proves that stiffened ship panels can be engineered into lighter geometries while minimising internal welding operations within confined spaces, establishing a scalable strategy for cost-efficient production.
4. The significance of this research lies in its pioneering shift from traditional manual-centric ship design to a prescriptive, multi-disciplinary Design for Automation (DfA) framework, bridging the gap between robotic kinematics and naval architecture. The primary contributions of this work are: (1) identifying the elevated (on-stiffener) configuration as the optimal robot position to maximise transversal mobility and enable autonomous, rail-guided bay-to-bay transitions; (2) formulating three parametric geometric rules (Rules 1, 2, and 3) that define the critical 950 mm vertical clearance necessary to eliminate manipulator collisions;

and (3) validating this co-design on a 7,700 DWT product tanker using ANSYS FEA. Under extreme hogging and hydrostatic loads, the DfA-compliant profile substitutions successfully preserved structural integrity, resulting in a minor 10.19% stress increase (safely below yield) and a negligible 0.66% change in deformation. This methodology provides a validated, low-risk and robust engineering template for transitioning to Shipbuilding 4.0.

5. The ultimate contribution of this dissertation is the execution of an integrated Multi-Objective Structural Optimisation (MOSO) framework that delivers an 18.15% reduction in structural mass while expanding the robot's vertical working envelope to a safe, collision-free clearance. Proving outstanding numerical precision (error margin below 0.5%), the resulting scantlings strictly comply with IACS CSR and Lloyd's Register (LR) codes. It satisfies the 175 MPa stress limits through compensatory thickening and secures structural safety with a robust 1.1306 buckling load multiplier, demonstrating that embedding robotic operational limits into early-stage Design for Manufacturing and Assembly (DFMA) principles is a reliable strategy for modern shipbuilding.

8.3 Future Works

While this research establishes a foundation for automated shipbuilding design, several avenues remain open for future academic and industrial exploration:

1. Future iterations of the framework could integrate machine learning algorithms (e.g., Deep Reinforcement Learning) to allow the robotic system to dynamically alter its path inside confined spaces to compensate for physical

structural tolerances and thermal distortions induced during the actual welding process.

2. Expanding the framework from a single-manipulator evaluation to a cooperative multi-robot system. This requires optimising the spatial constraints to allow two or more robots to perform synchronised welding within the same double-bottom bay without colliding with each other.
3. Implementing the optimised geometric profiles into a physical shipyard pilot test, utilising advanced seam-tracking sensors (such as laser vision systems and arc sensors) to validate the virtual cycle time and energy consumption models against real-world manufacturing data.
4. Adapting the developed VPF and optimisation mathematical models to other challenging areas of naval architecture, such as narrow wing tanks, side shells, corrugated bulkheads, and offshore wind turbine jacket foundations.

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