Design for Production

A Decision-Support Framework for Early-Stage Cost Reduction in One-Off Superyacht Hull Structures

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in the specialization of Ship Design

Design for Production – A Decision-Support Framework for Early-Stage Cost Reduction in One-Off Superyacht Production

By

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Performed at

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Preface

This thesis presents the results of my graduation project in the MSc programme Marine Technology at Delft University of Technology. The research was carried out at Scheepswerf Slob, part of Royal De Vries Shipbuilding (Feadship), and in cooperation with De Voogt Naval Architects. The project focuses on cost reduction strategies in one-off steel superyacht hull construction.

This project provided me with the privilege of working alongside highly experienced professionals within the superyacht industry. I am sincerely grateful for the opportunity to contribute, even modestly, to the further development and innovation of the Dutch maritime production sector at a time when efficiency and competitiveness are of increasing importance. Throughout this thesis, I gained valuable insight into the practical complexities of ship design and production, allowing me to bridge academic theory with real-world application.

I would like to express my sincere gratitude to my academic supervisor, Dr. Jeroen Pruijn, for his guidance, critical feedback, and academic support throughout this project. My appreciation also goes to Jason Tapsell for his supervision at Scheepswerf Slob and for sharing his industry expertise. I am particularly thankful to Gerard Schild for his daily guidance, practical insights, and his willingness to continuously engage in technical discussions. Furthermore, I would like to thank Jeroen Kortenoeven for granting me the opportunity to conduct this research within the organisation.

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Summary

The Dutch shipbuilding industry focuses on the construction of low-volume, high-value and technologically complex vessels. Within this context, the superyacht production sector is characterised by fully custom, one-off projects that combine strict aesthetic requirements with labour-intensive, hand-built manufacturing processes. As a result, superyacht construction is associated with high production costs, of which labour constitutes the dominant share. These characteristics highlight the importance of addressing producibility and cost implications during the early stages of structural design, where design freedom is still high and downstream production effort can be influenced most effectively.

This thesis examined how Design for Production (DfP) principles could be applied during the early design stages of one-off steel superyacht hull structures to identify key production cost drivers and support the reduction of hull construction costs by approximately 10–15%. Building on literature on Design for Production, cost assessment, and shipyard production processes, a structured methodology was developed to identify production-oriented Key Performance Indicators (KPIs) relevant to early-stage superyacht hull design and to support cost-informed structural decision-making.

To address the research objectives, a mixed-methods research approach was adopted, consisting of a qualitative phase and a quantitative phase. The qualitative phase focused on the evaluation, elimination, and prioritisation of DfP guidelines identified in the literature. This was achieved through an expert-based multi-criteria analysis, in which guidelines were assessed with respect to their importance, applicability, and expected cost reduction (IAR). This step enabled a context-specific filtering of broadly formulated DfP knowledge, reducing fragmentation and focusing the analysis on guidelines considered most relevant for one-off superyacht hull construction.

The prioritised guidelines formed the basis for the subsequent quantitative phase, in which production effort and cost were evaluated through the comparison of alternative structural scantling configurations, with a focus on part reduction and design simplification. Feature-Based Costing (FBC) was used to evaluate production-related KPIs and cost implications, while classical stiffened plate theory was applied in combination with Lloyd's Register class pressure envelopes to generate and assess a wide range of feasible scantling configurations. All evaluated design alternatives were constrained within a rule-consistent structural admissibility framework, ensuring that structural integrity and quality requirements were maintained throughout the analysis.

The results demonstrate that Design for Production principles can be effectively applied to one-off steel superyacht hull construction when qualitative producibility guidelines are systematically translated into quantitative early-stage structural design parameters. While expert-based prioritisation favours process-oriented measures due to their low perceived implementation risk, the quantitative analysis shows that design-oriented interventions have a substantially larger impact on production cost than anticipated based on qualitative assessment alone.

Production cost reduction was found to be primarily governed by a limited number of dominant production-oriented KPIs, of which part count emerged as the most influential due to its direct effect on welding effort, assembly time, and with that labour intensity, and production lead time. Coordinated increases in plate thickness and stiffener spacing reduced part count and resulted in panel-level production cost reductions of up to 23%, which translate to estimated overall production cost reductions of approximately 10–15% for hull stiffening. These reductions were achieved without compromising structural integrity or quality, confirming that the primary value of Design for Production lies in supporting informed early-stage design decision-making rather than identifying a single optimal solution.

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1

Introduction

The Netherlands has a long-standing tradition in shipbuilding, rooted in its favourable geographic position, extensive inland waterways and strong maritime orientation. As early as the nineteenth century, Dutch shipyards underwent a fundamental technological transition with the introduction of steam engines, marking a shift from craft-based shipbuilding towards industrial production requiring advanced engineering knowledge and the integration of mechanical systems [18]. Throughout the twentieth century, the sector further professionalised through the adoption of new production methods, such as steel construction and block construction, enabling Dutch shipyards to compete internationally in increasingly complex ship types. By the mid-twentieth century, the Netherlands ranked among the leading shipbuilding nations in Europe, demonstrating both technological capability and organisational maturity [2].

While large-scale, volume-driven shipbuilding gradually moved to lower-cost regions abroad, the Dutch maritime manufacturing industry repositioned itself towards high-value, low-volume segments. This historical trajectory laid the foundation for a specialised industrial ecosystem focused on complex, custom-built vessels, a characteristic that remains central to the contemporary Dutch superyacht production industry [22].

1.1. The Superyacht Production Industry

The global superyacht industry represents a distinct niche within the wider shipbuilding sector, characterised by low production volumes, high capital value, and a strong emphasis on customisation. Superyachts are commonly defined as yachts exceeding 24 metres in length and are predominantly realised as one-off or very small-series projects for private owners. In contrast to commercial shipbuilding, where standardisation and economies of scale dominate, superyacht construction is driven by bespoke requirements, aesthetic considerations, and owner-specific demands.

Within this global context, the Netherlands occupies a leading position in the construction of large and highly complex superyachts. The related Dutch shipyards specialise in vessels that require advanced engineering, tight integration between disciplines, and extensive craftsmanship. In 2024, the Netherlands was the world's largest producer of newly built superyachts exceeding 80 metres in length, highlighting its strong position in the upper segment of the market [1]. Approximately 70% of Dutch superyacht production consists of fully custom-designed vessels, reflecting the dominance of one-off production within the sector [1].

The Dutch superyacht industry is characterised by a highly specialised and interconnected production ecosystem. Shipyards operate in close collaboration with a dense network of suppliers, engineering firms, and subcontractors, many of whom are involved in multiple projects simultaneously. This ecosystem-based organisation enables the realisation of technically complex vessels, but also creates strong interdependencies between design, engineering, and production activities [22].

From a production perspective, superyacht construction offers limited opportunities for standardisation and is therefore inherently labour intensive . Despite the extensive scope and level of customisation, overall project lead times are relatively short compared to the complexity of the vessels produced. This results in tightly constrained production schedules, requiring careful coordination between parallel engineering, fabrication, and assembly activities. These characteristics define the industrial context in which production-oriented design challenges the superyacht sector.

1.2. Problem Context and Industry-wide Relevance

The competitive position of the Dutch superyacht production industry is increasingly under pressure due to a combination of production cost factors and rising project complexity. Compared to major shipbuilding nations, the Netherlands faces relatively high labour, energy, and regulatory costs, which directly affect production-intensive industries such as shipbuilding [22]. These cost disadvantages are particularly pronounced in the superyacht sector, where vessels are predominantly built as custom, one-off projects and opportunities for cost reduction through standardisation are inherently limited [1].

At the same time, market dynamics within the superyacht industry are characterised by continuously increasing owner demands. Clients increasingly require higher levels of customisation, advanced onboard systems, and complex architectural features, while simultaneously imposing strict constraints on weight, performance, and overall vessel efficiency [1]. These competing requirements result in designs with a high degree of structural and organisational complexity.

From a production perspective, increasing design complexity translates directly into higher labour intensity. The extensive use of bespoke components reduces repeatability and limits the applicability of standard production methods, leading to increased assembly effort, more complex coordination between disciplines, and a higher sensitivity to rework [4, 7]. As labour constitutes a substantial share of total construction costs in high-wage economies, these effects disproportionately impact Dutch shipyards [22].

Industry experts indicate that the cost structure of one-off superyacht construction differs fundamentally from that of series-built vessels. Interviews with senior management in the Dutch superyacht sector suggest that labour costs typically account for approximately 80–85% of total construction costs, with materials representing the remaining share [16].

In addition, typical production costs for complex vessels, such as custom superyacht structures, can reach approximately €100–€140 per tonne in the Netherlands. This implies that steel production costs in the superyacht sector are roughly five times higher than those observed in series-production environments. For comparison, large dry bulk cargo vessels produced in high-repeatability shipyards are often reported to exhibit fabrication costs in the order of €25 per tonne. These pronounced differences are primarily attributable to the limited repeatability inherent to one-off construction, the high level of manual labour involved, and the absence of standardised production sequences.

Together, these factors highlight a structural vulnerability of the Dutch superyacht sector to rising labour costs and increasing design complexity. In high-wage economies, such cost structures amplify the economic impact of additional engineering effort, bespoke detailing, and late design changes. These challenges are not confined to individual companies but are characteristic of the Dutch superyacht production industry as a whole, motivating the need for systematic approaches to production-oriented design decision-making.

1.3. Design for Production as a Conceptual Framework

The construction of superyachts represents a highly complex engineering endeavour, combining structural design, production planning and cost control within a predominantly one-off manufacturing environment. Increasing owner demands for size, performance and customisation have further intensified this complexity, placing significant pressure on designers and shipyards to manage producibility and cost already during the early design stages.

To address such challenges, design philosophies have been developed that aim to incorporate life-cycle knowledge as early as possible in the design process, in line with the well-known freedom of design curve. One of the most influential of these philosophies is Concurrent Engineering (CE), which emphasises the early availability and integration of knowledge from manufacturing, cost, quality, and operational domains alongside technical design activities [13, 26].

In shipbuilding, this perspective is particularly relevant due to the strong influence of early design decisions on downstream production effort and cost, while the ability to influence these outcomes rapidly decreases as the design progresses [7, 31]. Within this context, Concurrent Engineering (CE) can be understood as the early and parallel development of design and engineering information across multiple disciplines, enabling downstream activities such as production planning, procurement, and fabrication preparation to commence before the overall ship design is fully finalised. While this approach can significantly reduce overall lead time, it also implies that engineering information is developed under a higher degree of uncertainty, and consequently that design changes tend to occur more frequently.

Building on the principles of Concurrent Engineering, Design for X (DfX) provides a structured translation of early life-cycle knowledge into design-oriented methodologies that explicitly target specific downstream objectives, such as producibility, assemblability, and cost efficiency [7, 14].

Within this study, Concurrent Engineering is not applied as a formal methodology, but serves as a conceptual basis that motivates the early consideration of production-related design aspects. This perspective directly underpins Design for Production (DfP), which focuses on improving buildability and cost predictability by explicitly considering production constraints, process characteristics and labour intensity during early design stages [4, 7].

In serial manufacturing environments, DfP is commonly applied through standardisation, modularisation and process optimisation. However, the direct transfer of such approaches to superyacht construction is limited by the bespoke nature of the product, the dominance of labour-intensive processes and the central role of aesthetics [10, 13]. As a result, Design for Production in one-off shipbuilding cannot rely on prescriptive solutions, but must instead support informed design decision-making that reduces unnecessary structural complexity while preserving design freedom and quality.

Given the strong influence of early-stage design decisions on downstream production effort and cost, particularly in steel hull construction, Design for Production provides a relevant conceptual framework for addressing the competitive challenges faced by the Dutch superyacht industry [4, 7].

1.4. Problem Statement

The Dutch superyacht industry operates within a high-value, low-volume production environment that is characterised by one-off construction, high labour intensity and increasing design complexity. As a result of rising labour, energy and material costs, combined with growing owner-specific requirements, superyacht hull construction in the Netherlands has become increasingly sensitive to inefficiencies in design and production.

Despite the significant influence of early-stage design decisions on downstream production effort and costs, current design and engineering processes insufficiently account for production constraints and manufacturability during the initial phases of hull development. Design choices are primarily driven by performance, aesthetics and functionality, while the implications for fabrication complexity, assembly effort and cost predictability are often only addressed at later stages. In a labour-dominated cost structure, such late consideration of production aspects leads to avoidable rework, increased coordination effort and elevated construction costs.

While various Design for X methodologies address manufacturability and cost reduction in manufacturing industries, their effectiveness within the context of one-off superyacht hull construction remains largely unverified. Most of these methodologies have been developed and validated for series-built or commercial vessels, which are subject to fundamentally different design drivers, production volumes, and regulatory frameworks than custom-built steel superyachts. As a result, it remains unclear to what extent these approaches can be transferred to, and provide tangible benefits for, the early design and engineering phases of superyacht hull construction. This uncertainty limits the ability of Dutch shipyards to confidently apply production-oriented design principles to systematically influence hull construction costs and predictability at a stage where design freedom is still high and design changes are relatively inexpensive.

1.5. Research Objective

The objective of this thesis is to investigate how Design for Production principles can be applied during the early design and engineering phases of one-off superyacht hull construction in order to improve cost predictability and reduce construction effort. The research aims to develop and evaluate a structured approach for Design for Production within the context of Dutch superyacht shipbuilding, with specific attention to standardisation opportunities and part reduction, while maintaining the required standards of design quality, technology and craftsmanship.

1.6. Research Questions

Based on the problem outlined in the previous section, this research aims to investigate how Design for Production (DfP) principles can be systematically applied during the early design stages of one-off superyacht hull construction in order to improve cost predictability and reduce production effort. To structure this investigation, one main research question (MRQ) is formulated, supported by a set of subordinate research questions (RQs). Together, these questions guide the research from a theoretical exploration of existing Design for Production knowledge towards its practical application and quantitative evaluation within the context of highly customised superyacht construction.

MRQ:*"To what extend can established Design for Production principles in shipbuilding be applied to reduce hull production cost in highly customised, one-off superyacht construction through early-stage structural design simplification, while maintaining structural integrity and quality?"*

The subordinate research questions are structured to follow a logical progression of the process used in this thesis. The first research question focuses on identifying relevant Design for Production–oriented Design for X principles and guidelines as reported in shipbuilding literature. Building on this theoretical foundation, the second research question addresses the relevance and prioritisation of these guidelines specifically for one-off superyacht hull construction, incorporating expert judgement to account for the unique characteristics of this production environment. The third research question then investigates how the prioritised guidelines can be translated into concrete early-stage structural design parameters and modelling assumptions that are suitable for quantitative analysis. Subsequently, the fourth research question examines which production-oriented Key Performance Indicators (KPIs) are most influential in driving production cost reduction through the reduction of structural complexity, and how their impact can be quantitatively assessed during the early design phases. Finally, the fifth research question explores how the interaction between cost and other key performance indicators can be used to support informed decision-making in early-stage structural design, thereby enabling designers to balance production efficiency with structural performance and quality requirements. The formulated research questions are presented below.

RQ1: *"Which Design for Production–oriented Design for X principles and guidelines are identified in shipbuilding literature?"*

RQ2: *"Which of these Design for Production guidelines are considered most relevant for highly customised, one-off superyacht hull construction, and how can they be systematically prioritised based on expert judgement?"*

RQ3: *"How can prioritised Design for Production guidelines be translated into concrete early-stage structural design parameters and modelling assumptions suitable for quantitative evaluation, while maintaining structural integrity and appropriate quality control constraints?"*

RQ4: *"Which production-oriented Key Performance Indicators are most influential in driving production cost reduction through structural complexity reduction, and how can their impact on early-stage structural design be quantitatively assessed?"*

RQ5: *"To what extent does the integrated structural optimisation and Feature-Based Costing–based KPI evaluation framework enable early-stage structural complexity reduction while achieving measurable production cost savings without compromising structural integrity?"*

1.7. Research Approach

The research is structured in two main phases to systematically assess the role and impact of Design for Production (DfP) principles in the early-stage structural design of one-off superyacht hulls. In particular, both the relevance of individual DfP guidelines and their potential impact on production cost and structural complexity remain uncertain within this highly customised context.

For this reason, the first phase of the research focuses on the systematic identification and prioritisation of DfP guidelines applicable to shipbuilding, based on literature and expert judgement. This prioritisation step serves to reduce the design space and to establish a focused set of production-oriented design measures for further analysis. The second phase subsequently investigates the potential impact of the highest-priority DfP guidelines through quantitative evaluation. By translating these guidelines into early-stage structural design parameters and modelling assumptions, the study aims to assess their influence on production-related performance indicators, such as production effort and production cost.

Given the exploratory nature of the first phase and the evaluative character of the second phase, the study adopts a mixed-methods research approach combining qualitative and quantitative methods. The qualitative phase focuses on the identification, assessment and prioritisation of Production–oriented Design for X guidelines applicable to shipbuilding.

A structured literature review is conducted to identify existing DfP principles and guidelines within the shipbuilding domain, addressing RQ1. These guidelines are subsequently assessed and prioritised for their relevance to highly customised, one-off superyacht hull construction through expert judgement, addressing RQ2. This prioritisation step ensures that the subsequent quantitative analysis focuses on production-oriented design measures that are considered most influential within the studied industrial context.

The quantitative phase translates the prioritised DfP guidelines into concrete early-stage structural design parameters and modelling assumptions suitable for numerical evaluation, addressing RQ3. A cost-based structural evaluation framework is developed to assess the influence of design-oriented DfP measures on production-related Key Performance Indicators (KPIs), with a particular focus on structural complexity and production cost. This framework enables a systematic exploration of the design space and supports the quantitative assessment of trade-offs between cost, structural performance and other relevant KPIs, addressing RQ4 and RQ5.

The quantitative analysis is conducted using simplified early-stage structural models and rule-based constraints to ensure relevance for preliminary design applications. Uncertainty in key parameters is explicitly considered to reflect the inherent variability present in early design stages. The developed framework and results are validated through internal consistency checks and comparison with established design practices to ensure methodological robustness.

A detailed description of the applied methods, assumptions and analysis procedures is provided in Chapter 3.

1.8. Scope and Limitations

This research focuses on the application of Design for Production principles to the early-stage structural design of steel superyacht hulls within a one-off production environment. The scope of the study is deliberately limited to the primary hull structure, including longitudinal and transverse structural elements, plating and stiffening systems, as these components have a dominant influence on structural complexity, fabrication effort and production cost during hull construction.

The research is confined to the early design and engineering phases, where key structural parameters and design decisions are defined and where the potential to influence downstream production effort and cost is greatest. Detailed engineering, production planning and execution-phase considerations fall outside the scope of this study. Similarly, the research does not address non-structural systems such as outfitting, interior construction, mechanical installations or electrical systems, as these are subject to different design drivers and production processes.

From a methodological perspective, the study adopts a case-based approach representative of the Dutch superyacht industry. The developed Design for Production framework and quantitative evaluation are intended to provide general insights into production-oriented design decision-making rather than to produce statistically representative benchmarks. Cost figures, labour ratios and production characteristics used in the analysis are therefore treated as indicative and context-specific.

The quantitative analysis is based on simplified early-stage structural models and rule-based constraints to ensure applicability during preliminary design. As a consequence, the results do not aim to replace detailed structural analyses or class approval calculations, but rather to support comparative assessment and informed decision-making in the early design stages. Uncertainty is explicitly considered; however, not all sources of variability inherent in full-scale production projects can be captured.

Finally, while the research seeks to identify opportunities for reducing structural complexity and improving cost predictability, it does not aim to prescribe specific design solutions or guarantee absolute cost reductions. The findings should be interpreted as decision-support insights that contribute to improved production-oriented design practices within the context of one-off superyacht construction.

2

Literature Review

This chapter provides the theoretical foundation for the research by reviewing methodologies that integrate production considerations into engineering design. Particular attention is given to Concurrent Engineering and Design for X (DfX), as these approaches emphasise the impact of early design decisions on downstream production effort and cost.

In addition, cost assessment methods used in shipbuilding are discussed to establish how potential production improvements can be evaluated. The chapter concludes by positioning Design for Production within the broader literature and identifying the research gap addressed in this thesis.

2.1. Background Information

Through the centuries, shipbuilding has evolved into a complex process, combining multiple disciplines in engineering, design, and management. To address this complexity, researchers, designers, and engineers have explored what makes the development, production, and operation so complex. Improving all phases of the lifecycle required the integration of knowledge from each stage. This approach is now known as Concurrent Engineering and forms the foundation for Design for X (DfX) methodologies.

This chapter provides an overview of the principles and ideas behind these methodologies, along with the rules and guidelines developed over the years. Next, it presents an overview of cost assessment methods in the shipbuilding industry, offering an initial perspective on how to measure potential improvements from applying the discussed DfX principles.

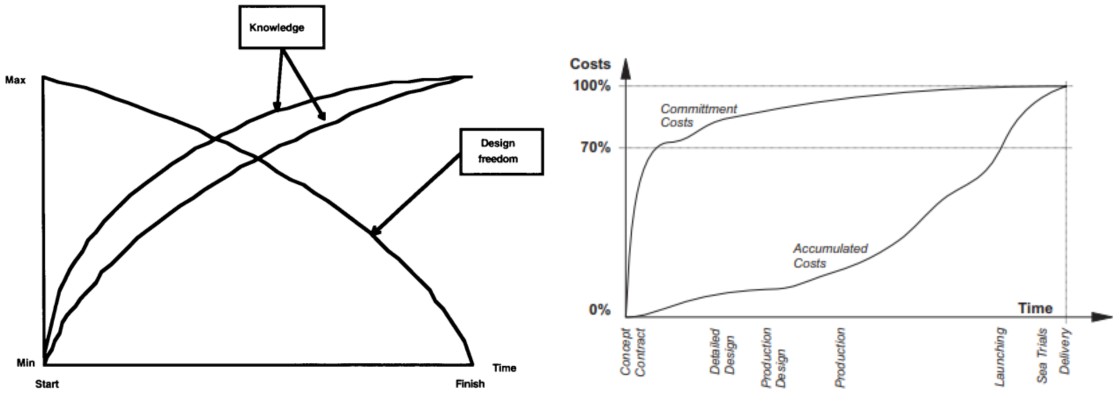
2.1.1. Concurrent engineering

Concurrent Engineering (CE) provides the conceptual foundation for Design for X (DfX) methodologies by promoting the early integration of production, cost, quality, and lifecycle considerations into engineering design. In shipbuilding, this perspective is particularly relevant due to the strong influence of early design decisions on downstream production effort and cost [7].

A widely adopted definition of CE describes it as the earliest possible integration of organisational knowledge and experience across design and production disciplines in order to achieve high-quality products at reduced cost and development time [31]. This emphasis on early-stage decision-making aligns directly with the objectives of Design for Production.

As illustrated in Figure 2.1, design freedom decreases rapidly as project knowledge increases, while the majority of production cost is committed during early design phases. This relationship highlights the importance of incorporating production-oriented considerations at an early stage, where design choices have the greatest leverage.

In the present study, Concurrent Engineering is not applied as a formal methodology, but serves as a conceptual basis for motivating early-stage integration of production-related design considerations. This perspective directly underpins the Design for Production principles discussed in the following sections.



(a) Knowledge and freedom of design

(b) Commitment costs [7]

Figure 2.1: Impact of early knowledge

Design for X theory

While Concurrent Engineering provides the overarching development framework, Design for X (DfX) offers structured methodologies for incorporating downstream considerations into engineering design. DfX approaches translate lifecycle objectives into concrete design rules and guidelines that can be applied during early design stages [14].

In practice, DfX methodologies are implemented through the formulation of design guidelines, checklists, and evaluation criteria, often supported by multidisciplinary reviews and expert judgement. These mechanisms enable designers to systematically consider production-related implications during early design decision-making.

Although a wide range of DfX methodologies has been proposed in literature, not all are equally relevant for early-stage, production-oriented structural design. The present study therefore focuses on Design for Production and closely related design-oriented DfX subsets that directly influence structural complexity and production effort. Other DfX methodologies are considered only insofar as they provide contextual background for positioning Design for Production within the broader DfX landscape.

An overview of the selected design-oriented DfX methodologies and their primary design considerations is provided in Table 2.1. These methodologies form the theoretical basis for identifying and structuring the Design for Production guidelines evaluated in the subsequent qualitative and quantitative analysis.

Table 2.1: Design-oriented Design for X methodologies relevant to production-oriented structural design

Design for	Scope	Primary design considerations	Key references
Design for Production (DfP)	Product	Minimise total production effort through early design decisions, considering fabrication, assembly, welding, logistics, and quality control as an integrated whole.	[7, 4, 6]
Design for Assembly (DfA)	Product	Reduce assembly effort by minimising part count, joints, and handling operations, and by simplifying assembly sequences.	[5, 32, 21]
Design for Manufacturing (DfM)	Product	Facilitate efficient and robust fabrication by simplifying manufacturing operations, welding procedures, and tolerances.	[5, 7, 32]
Design for Simplicity (DfS)	Product	Reduce structural complexity by limiting the number of elements, interfaces, and geometric variation in structural design.	[7, 10, 11]

2.1.2. Cost Assessment

Cost estimation in shipbuilding, especially for Engineering-to-Order (ETO) projects, requires methods that can handle limited data in early design stages, and the complexity of custom designs. Several approaches are used, each with its own way of working, strengths, and limitations.

Overview of cost assessment methods

Table 2.2: Strengths and weaknesses of cost estimation and producibility methods

Group	Method	Strengths	Weaknesses
Top-down	Intuitive Method (IM)	Fast; flexible; uses expert knowledge; works with limited data; good for early forecasts and cross-checks [3, 9, 7]	Subjective; inconsistent; not traceable; bias risk; “black box”; accuracy depends on estimator [3, 7]
	Case-Based Reasoning (CBR)	Rapid; reuses company knowledge; transparent logic; adapts to small changes; avoids repeated mistakes [3, 7]	Needs reliable case base; weak for novel designs; similarity judgement subjective; declining use [3, 7]
	Parametric Method (PM)	Quick; repeatable; objective; highlights cost drivers; supports trade-offs [3, 7]	“Black box”; needs accurate data; correction factors add subjectivity; weak for one-offs [3, 7]
Bottom-up	Feature-Based Costing (FBC)	Clear link between features and cost; supports design-to-cost; CAD/CAM integration; enables automation [3, 7]	Needs detailed design; high setup effort; less useful very early [3, 7]
	Activity-Based Costing (ABC)	Detailed view of indirect/overhead costs; links costs to activities; improves transparency [3]	Data-heavy; complex to maintain; limited use early-stage [3]
	Group Technology (GT)	Groups similar parts; reuses historic data; supports modularisation; complements FBC [3, 7]	Less suited to unique designs; needs accurate coding; depends on consistent history [3, 7]
Computer-based	Fuzzy Logic (FL)	Handles uncertainty; captures expert knowledge; transparent; works without large datasets [7, 3]	Needs reliable expert input; careful rule/membership design; hard to verify for new tech [7, 3]
	Neural Network (NN)	Finds complex patterns; adapts with new data; strong for repetitive families [7, 3]	“Black box”; needs large datasets; weak for one-offs; heavy training effort [7, 3]
	Production Simulation (PS)	Realistic production models; finds bottlenecks; supports planning/optimisation; visual [7]	Time/resource-intensive; needs skilled modellers; input data must be high quality [7]

While these methods provide a foundation for linking design to production costs, their adaptation to bespoke superyacht hulls is still uncertain. Section 2.3 therefore reviews recent research efforts that have sought to bridge this gap by applying DfX principles and cost assessment methods to practical contexts.

2.2. Research Methodology

For this literature review, academic databases such as Google Scholar and Scopus were used to identify relevant publications. Table 2.4 provides an overview of the main search terms applied and the number of results retrieved from each database. Notably, while Google Scholar returned significantly more results, these were often less targeted and included unrelated literature, requiring additional screening.

Due to the large volume of search results, a maximum of ten pages per search string was screened based on title relevance. Over 100 papers were downloaded and reviewed using their title and introduction. From these, 33 sources were selected for the literature review: 27 high-relevance sources form the core review, while 6 provide background and introductory context.

Table 2.4: Number of results per search engine

Search term	Scopus	Google Scholar
"Design for Production" AND ("Shipbuilding" OR "Ship design")	11	388
("Design for X" OR "DFX") AND ("Shipbuilding" OR "Ship design")	3	227
("Design for Manufacturing" OR "DFM") AND ("Shipbuilding" OR "Ship design")	2	340
("Design for Assembly" OR "DFA") AND ("Shipbuilding" OR "Ship design")	0	200
"Design for Flexibility" AND ("Shipbuilding" OR "Ship design")	0	50
"Design for Modularity" AND ("Shipbuilding" OR "Ship design")	0	84
"Lean Manufacturing" AND ("Shipbuilding" OR "Ship design")	32	2400
"Six Sigma" AND ("Shipbuilding" OR "Ship design")	12	2130

Overview of reviewed literature -2cm-2cm

Table 2.5: Literature overview — DfX and Concurrent Engineering

Year	Title	$_1$Journal; $_2$Publisher; $_3$Source	Focus / Contribution	Applicability
1990	Design for X (DFX): *Key to Competitive, Profitable Products.* Gatenby, D. A., Foo, G.	$_1$AT&T Technical Journal	DFX principles for competitiveness	Foundational for DFX concepts
1991	Concurrent Engineering and Design for Manufacture of Electronics Products. Shina, S. G.	$_1$Book; $_2$Van Nostrand Reinhold	Early work on CE and DFM integration	General CE framework
1994	Product Design for Manufacture and Assembly. Boothroyd, G.	$_1$Computer-Aided Design; $_2$Butterworth-Heinemann Ltd	Core DfMA methodology	Broad manufacturing relevance
1997	Concurrent Engineering in Ship Design. Elvekrok, D. R.	$_1$Journal of Ship Production	CE applied to ship design process	Shipbuilding-specific CE
2000	Design for Assembly: *Influencing the Design Process.* Dalgleish et al.	$_1$Journal of Engineering Design; $_2$Taylor & Francis	DfA's role in early-stage design	General manufacturing
2002	Design and Prototyping of Knowledge Management Software for Aerospace Manufacturing. Hale, P. et al.	$_1$ISPE Int. Conf. on Concurrent Engineering; $_2$Cranfield Univ.	Knowledge management in CE context	Relevant to CE knowledge transfer
2003	Process Planning: The Design/Manufacture Interface. Scallan, P.	$_1$Book; $_2$Butterworth-Heinemann	Foundational text on process planning	DfM and DfP concepts
2003	Complex Concurrent Engineering and the Design Structure Matrix Method. Yassine, A., Braha, D.	$_1$Concurrent Engineering: Research and Applications; $_2$Sage Publications	DSM for managing CE complexity	CE complexity management
2004	Considering Design for Production Principles in Ship Hull Design. Bertram, V.	$_1$Journal of Marine Engineering	Integrates DfP in hull form design	Direct shipbuilding relevance
2009	Multi-Criteria Decision Support for Cost Assessment Techniques in Shipbuilding Industry. Caprace, J. D., Rigo, P.	$_1$Conference Proceedings	Evaluates cost assessment methods	Shipbuilding cost methods
2010	A Real-Time Assessment of the Ship Design Complexity. Caprace, J. D.	$_1$Computer-Aided Design; $_2$Elsevier	Complexity metric for ship design	Supports complexity measurement
2010	A Complexity Metric for Practical Ship Design. Caprace, J. D., Rigo, P.	$_1$Conference Proceedings	Quantifies structural complexity	Shipbuilding-specific metric
2010	Cost Effectiveness and Complexity Assessment in Ship Design within a Concurrent Engineering and "Design for X" Framework. Caprace, J. D.	$_1$PhD Thesis; $_2$Université de Liège	In-depth DFX, CE, and cost research	Directly relevant
2011	Managing Complexity in Aircraft Design Using Design Structure Matrix. Shekar, B., Mani, M., Shankar, R.	$_1$Concurrent Engineering: Research and Applications; $_2$Sage	DSM for managing design complexity	Complexity insights for CE
2011	Investigation of the Applicability of DfX Tools During Design Concept Evolution: A Literature Review. Chiu, M.-C., Kremer, G. E.	$_1$ResearchGate	Reviews DfX applicability during concept design	General DfX stage-gate relevance
2014	A Simplified Approach to Design for Assembly. Moultrie, J., Maier, A. M.	$_1$Journal of Engineering Design; $_2$Taylor & Francis	Practical team-based DfA approach	Small/medium assembly processes
2014	Analysis and Integration of Design for X Approaches in Lean Design as Basis for a Lifecycle Optimized Product Design. Dombrowski et al.	$_1$Elsevier	Integrates DfX in Lean Design using CPM	Lifecycle cost/waste optimisation
2019	A Systematic Review of Design for X Techniques from 1980 to 2018: *Concepts, Applications, and Perspectives.* Chaouni Benabdellah et al.	$_1$The International Journal of Advanced Manufacturing Technology	Broad DfX methods review	General; not shipbuilding-specific
2019	Modularity in the Design and Construction of Naval Vessels. Daidola, J. C.	$_1$Proc. of SNAME Maritime Convention; $_2$SNAME	Modularity in naval ship design	Modularity concepts

Continued on next page

Year	Title	$_1$Journal; $_2$Publisher; $_3$Source	Focus / Contribution	Applicability
2019	Design for Modularity. Erikstad, S. O.	$_1$A Holistic Approach to Ship Design (Book Chapter); $_2$Springer	Framework for modular design	Ship design modularity
2020	Shipbuilding Management. Bruce, G.	$_1$Book; $_2$Springer	Overview of modern shipbuilding management	General shipyard operations
2021	An Approach to Measuring Ship Design Complexity. Ebrahimi, A. et al.	$_1$Trans RINA	Quantitative approach for complexity	Supports hull design trade-offs
2022	Design for Manufacturing (DFM): *A Sustainable Approach to Drive the Design Process from Suitability to Low Cost.* Moeeni et al.	$_1$Int. Journal on Interactive Design and Manufacturing; $_2$Springer	Proposes IAR index for DfM factors	General manufacturing; adaptable
2023	Lean Six Sigma Methodology for Waste Reduction: A Literature Review. Priyanda, E. et al.	$_1$IOP Conference Series: Materials Science and Engineering	Reviews Lean Six Sigma for waste reduction	Relevant for process improvement
2023	Industry 4.0 and Lean Six Sigma Integration in Manufacturing: A Literature Review. Skalli, A. et al.	$_1$Heliyon	Combines Industry 4.0 with LSS framework	Modern process optimisation
2024	Modularity to Support the Design of a Super Yacht. Marcus, H. J. J.	$_1$Technical Report; $_2$Delft University of Technology	Modularity in superyacht design	Directly relevant for superyachts
2024	Are Current Shipbuilding Cost Estimation Methods Ready for a Sustainable Future? Alblas, G., Pruijn, J.	$_1$International Shipbuilding Progress	Reviews current cost estimation methods	Directly relevant for cost modelling

Overall, the reviewed literature establishes a strong theoretical basis for integrating production considerations into early-stage ship design and highlights the variety of available cost assessment approaches. However, the direct application of these methodologies to one-off steel superyacht hull construction remains limited in both scope and validation.

The following section therefore examines the current State of the Art, focusing on recent research efforts that attempt to operationalise Design for Production principles and cost assessment methods within practical shipbuilding contexts.

2.3. State of the Art

Building on the principles of Design for X (DfX), several researchers have developed methods to integrate production-oriented considerations into ship design and construction [4, 8, 20, 12, 21]. These studies aim to improve cost awareness and producibility by linking design decisions to downstream production effort. In parallel, research by Caprace [7] and Bertram [4] has focused more explicitly on quantitative cost assessment frameworks that evaluate the impact of design-based improvements on production cost.

This section reviews and critically evaluates these contributions with respect to their relevance for bespoke steel superyacht hull construction. Section 2.3.1 discusses representative applications that connect design choices to production effort and cost. Section 2.3.2 synthesises the most relevant Design for X principles and guidelines, followed by a comparative discussion (Section 2.3.3) and a gap analysis (Section 2.3.4) that positions the present research.

2.3.1. Relevant applications from literature

A range of methodological contributions in shipbuilding and manufacturing provide tools to relate design decisions to production effort and cost. This subsection reviews representative approaches, focusing on their applicability to one-off steel superyacht hulls.

Design for Production combining top-down and bottom-up cost assessment Bertram [4] proposes an integrated hull design approach that explicitly accounts for producibility alongside hydrodynamic performance. Central to this approach is the recognition that local geometric characteristics, particularly double curvature, are major drivers of forming effort and production cost. By identifying curvature-intensive regions early, designers can anticipate costly forming and straightening operations.

The method combines a top-down cost estimation, based on global hull parameters, with a bottom-up approach that incorporates detailed features such as plate count, panel size, and weld length. This dual strategy enables early trade-off studies while allowing increased accuracy as design detail becomes available. Although developed primarily for early-stage design, the approach illustrates how geometric complexity can be translated into cost-relevant indicators. For superyacht hulls, where aesthetic curvature is often intentional, the method highlights opportunities to mitigate unnecessary production effort without compromising design intent.

Impact of DfM principles using IAR analysis Moeeni, Javadi, and Raissi [20] introduce the Importance–Applicability–Reduction (IAR) index to prioritise Design for Manufacturing principles based on expert judgement. Building on concepts from Failure Mode and Effects Analysis, the IAR method combines perceived importance, practical applicability, and expected cost reduction into a single prioritisation metric.

The study demonstrates that reducing part count and fastener use yields the highest potential cost savings, challenging the assumption that simple operational improvements are always most effective. While the method is generic and not specific to shipbuilding, its structured prioritisation approach is highly relevant for bespoke superyacht construction, where design changes must balance cost impact, feasibility, and risk. However, the method relies strongly on expert input and does not provide quantitative validation of the prioritised principles. The IAR approach therefore offers a structured qualitative prioritisation mechanism, which could potentially be strengthened through combination with quantitative evaluation methods.

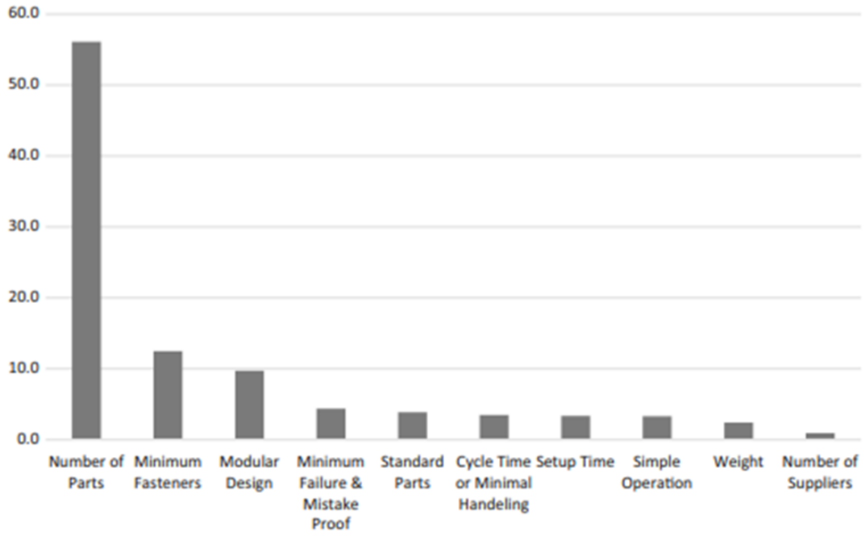


Figure 2.2: Result for IAR scoring from DfM principles study [20]
for the manufacturing industry.

Feature-Based Costing for shipbuilding Caprace [7] developed a Feature-Based Costing (FBC) framework for shipbuilding that links geometric design features extracted from CAD models to production cost through Cost Evaluation Relationships. Organised using the Ship Work Breakdown Structure, the framework enables aggregation of cost from individual plates and welds to larger assemblies and the full vessel.

A key strength of FBC is its ability to provide iterative cost feedback during conceptual and preliminary design, when design freedom is high. This makes the method particularly suitable for supporting Design for Production decisions. However, its effectiveness depends on the availability of detailed production data and reliable cost norms, which are often limited in bespoke superyacht construction. Moreover, structural complexity effects are not explicitly modelled, potentially reducing accuracy when costs are extrapolated across highly non-uniform hull structures. These limitations indicate that Feature-Based Costing could benefit from complementary indicators that explicitly represent structural complexity.

Fuzzy straightening cost assessment As an extension of the FBC framework, Caprace [7] introduces a fuzzy-logic-based metric to estimate straightening effort, a significant but uncertain cost driver in steel hull construction. By combining geometric deviation data with expert-defined fuzzy rules, the method provides probabilistic estimates of straightening man-hours.

The main contribution of this approach lies in its explicit treatment of uncertainty and variability in production effort. While the method adds modelling complexity and requires expert calibration, it illustrates how non-deterministic production effects can be incorporated into early-stage cost assessment. For bespoke superyacht hulls, where aesthetic requirements can increase straightening effort, this insight is particularly relevant, even if fuzzy modelling is not applied directly in the present study.

Lean Design-based DfX methods Dombrowski, Schmidt, and Schmidtchen [12] propose a Lean Design approach that integrates DfX guidelines through a Characteristics–Properties Modelling framework. The method systematically links design parameters to lifecycle waste and customer value, supporting trade-off analysis across multiple design objectives.

While the framework provides a comprehensive qualitative structure for managing conflicting DfX guidelines, its application remains largely conceptual and lacks quantitative validation. As such, its direct applicability to early-stage structural optimisation in superyacht hulls is limited. Nevertheless, the work highlights the importance of structured guideline management and trade-off awareness, reinforcing the need for prioritisation mechanisms supported by quantitative evaluation. reduction.

Simplified Design for Assembly approaches Moultrie and Maier [21] present a simplified Design for Assembly method aimed at increasing industrial adoption through team-based, low-threshold tools. By combining structured desk analysis with direct observation of assembly processes, the approach enables cross-functional identification of assembly inefficiencies.

Although the method is primarily qualitative and validated in a limited industrial context, it demonstrates the value of involving production personnel early in design evaluation. For bespoke superyacht hull construction, the approach offers insights into organisational learning and feedback, but lacks the precision required for quantitative assessment of structural design alternatives.

Structural complexity metrics in ship design Caprace and Rigo [8] propose a quantitative structural complexity metric for ship design, decomposing total complexity into shape, assembly, and material components. The metric correlates calculated complexity scores with observed production man-hours, enabling identification of high-complexity regions within ship structures.

A key strength of this approach is its explicit link between design characteristics and production effort. However, the method requires calibration for specific ship types and production environments. Structural complexity can be represented through various production-related indicators, such as part count, weld length, and structural density, which are compatible with early-stage design contexts and available production data.

To systematically compare the identified applications and assess their relevance for early-stage cost-oriented Design for Production in one-off superyacht construction, a structured synthesis is presented in Table 2.6. The table evaluates each contribution across three analytical dimensions: cost assessment integration, Design for X (DfX) orientation, and process management implications. In addition, the key insights, methodological strengths, limitations, and potential applicability to bespoke steel hull production are summarised.

This overview enables identification of complementary strengths, methodological gaps, and opportunities for integration, thereby forming the conceptual foundation for the proposed framework.

Table 2.6: Overview of relevant applications and their relation to cost assessment, Design for X, and process management, including key insights, strengths, limitations, and potential applicability to bespoke superyacht hull construction

Application / Tool	Cost Assessment	DfX	Process Mgmt.	Key insights	Strengths	Limitations	Potential superyacht relevance
Bertram [4] Hull Developability	X	X (DfP)		Surface developability can reduce forming effort while maintaining hydrodynamic performance	Explicit link between geometry and production effort; supports early-stage trade-offs	Aesthetic curvature may dominate; limited benefit if complex geometry is essential	Potentially useful for early-stage cost–shape trade-offs, subject to aesthetic constraints
Moeeni, Javadi, and Raissi [20] IAR model		X (DfM)		Structured prioritisation of DfM principles highlights part and fastener reduction	Empirically grounded; simple implementation; supports decision structuring	Generic manufacturing context; sensitive to expert bias and respondent selection	Applicable if adapted with superyacht-specific criteria and expert input
Caprace [7] Feature-Based Costing	X	X (DfP/DtC)		CAD-derived features linked to cost via SWBS and CERs enable iterative feedback	Traceable cost structure; compatible with early design; integrates with CAD/-CAM	Data-intensive; early-stage input may be incomplete; complexity effects not explicit	Strong potential if supported by targeted data collection and supplementary complexity indicators
Caprace [7] Fuzzy straightening metric	X			Probabilistic estimation captures uncertainty in straightening effort	Reflects real production variability; complements deterministic cost norms	Requires expert calibration; increased modelling complexity	Relevant where straightening effort is significant and supporting data is available
Caprace and Rigo [8] Structural complexity metric	X	X		Shape, assembly, and material complexity correlate with production effort	Quantitative and yard-calibratable; identifies high-complexity hotspots	Requires calibration; excludes outfitting; risk of overinterpretation	Highly relevant for highlighting non-value-adding structural complexity when combined with cost models
Dombrowski, Schmidt, and Schmidtchen [12] Lean DfX framework		X	X	Structured mapping of DfX guidelines supports lifecycle trade-off analysis	Systematic organisation of guidelines; explicit trade-off handling	Conceptual; largely qualitative; limited industrial validation	Potentially relevant for managing trade-offs, but requires adaptation for steel hull design
Moultrie and Maier [21] Simplified DfA		X (DfA)		Team-based DfA enables identification of assembly inefficiencies	Low threshold; strong cross-functional engagement	Limited precision; validated in a single context	Useful for engaging production stakeholders, though limited for quantitative evaluation

In summary, the reviewed applications demonstrate that both Design for X methodologies and cost assessment approaches offer valuable, yet partial, insights into the relationship between design decisions and production performance. While several methods successfully link geometric or structural characteristics to production effort, and others provide structured prioritisation of producibility principles, these contributions remain largely fragmented and insufficiently tailored to the bespoke nature of superyacht hull construction.

In particular, limited integration exists between qualitative Design for Production guidance and quantitative evaluation methods capable of assessing structural and cost implications in early design stages. This fragmentation underscores the need to first clarify and prioritise production-oriented design guidelines specific to shipbuilding practice, before translating them into measurable design variables suitable for structured evaluation. The following subsection therefore examines established Design for Production guidelines in shipbuilding to identify principles that are most relevant for one-off superyacht hull construction.

2.3.2. Design for X principles and guidelines

As introduced in Section 2.1, Design for X (DfX) methodologies have been studied extensively over several decades within shipbuilding and related manufacturing disciplines. Across this body of literature, researchers have formulated a wide range of principles, rules, and guidelines aimed at improving producibility, quality, and cost effectiveness through early design decisions. An initial set of 42 guidelines was identified from the literature, reflecting the breadth of Design for Production–oriented knowledge developed for general shipbuilding practice.

To establish a coherent and transparent basis for further analysis, this initial set was first reviewed for overlap and conceptual redundancy. Closely related formulations were harmonised, and guidelines addressing the same underlying principle were consolidated. Following this consolidation, all 42 literature-derived guidelines were retained for contextual evaluation rather than being implicitly discarded.

To assess whether these guidelines are conceptually meaningful within the context of bespoke superyacht hull construction, a first-order relevance screening was performed. This screening evaluates guideline compatibility with the defining characteristics of superyacht construction, namely the dominant role of aesthetics, stringent quality expectations, demanding performance requirements, and the need for generous interior volumes. Performance and quality are treated as boundary conditions at this stage: guidelines that imply fundamental compromises in these aspects are considered incompatible with the superyacht context.

The purpose of this screening is not to establish a detailed prioritisation, but to determine whether a guideline is applicable to superyacht construction at all. As such, the screening functions as a conceptual sanity check that distinguishes between guidelines that can be meaningfully transferred from general shipbuilding literature and those that primarily prescribe global hull-form characteristics typical of commercial or series-built vessels.

Based on this relevance screening, 36 guidelines were identified as broadly compatible with the constraints and ambitions of bespoke superyacht hull construction and are retained for subsequent analysis. The remaining guidelines are explicitly documented as eliminated, to maintain traceability to the literature and transparency in the selection process. Both the retained and eliminated guideline sets are presented below.

It should be emphasised that this screening represents a literature-based assessment of contextual applicability rather than a judgement of guideline importance or effectiveness. At this stage, all retained guidelines are treated as conceptually valid contributions from the literature, forming the foundation for subsequent methodological steps in the research.

1. Incorporate detailed knowledge of yard facilities (cranes, workshops, transport routes) into the design process [4, 9, 6]
2. Apply work breakdown structures (system-, purchasing-, product-oriented) to organise production activities [4, 9, 6]
3. Form multi-disciplinary teams of design, production, and outfitting specialists to align decisions [4, 9, 6]
4. Eliminate the need for on-site decision-making or adjustments [7]
5. Include alignment features like position lines and identifiers on plates [7]
6. Incorporate accuracy and repeatability requirements for large-scale block construction and early outfitting [7]
7. Design parts to clearly indicate orientation and positioning [7]
8. Use parts that are easy to handle [7]
9. Design for maximum use of high-productivity tools (e.g. automatic welding, cutting) [7]
10. Locate side block erection joints above the bilge tangent and tank top to simplify fit-up [7]
11. Use feedback loops between production and design teams to improve producibility [4, 9, 6]
12. Prefer assembly in open spaces over confined areas (e.g. increase block size to avoid double-bottom work) [7]
13. Plan service routes and straight pipe runs for ease of pre-outfitting [7]
14. Ensure good accessibility and visibility during assembly [7]
15. Avoid hidden areas that increase rework [7]
16. Use standard processes wherever possible to ensure repeatability and consistent quality [7]
17. Plan outfitting sequence early to minimise congestion [7]
18. Establish unit breaks early, design repetitive blocks/modules, size blocks for crane limits [7]
19. Keep macro curvature within producable limits to reduce fairing [4, 9, 6]
20. Favour single curvature or developable surfaces; avoid double curvature [4, 9, 6]
21. Use straight frames, strakes aligned with primary framing, straight inner structures [4, 9, 6]
22. Simplify local panel curvature for easier forming [4, 9, 6]
23. Avoid overly thin plates that cause distortion and rework [7]
24. Minimise weld lengths through panel design [7]
25. Reduce total number of parts by integrating functions or modularising sub-assemblies [20, 7]
26. Allow parts to be inserted from above during assembly [7]
27. Balance aesthetic shapes with producibility [4, 9, 6]
28. Maximise use of standard plate and stiffener sizes to simplify purchasing and inventory [7]
29. Minimise need for reorientation of parts; use symmetrical designs where possible [7]
30. Design bilge strakes with the same thickness as bottom plates to reduce forming complexity [4, 9, 6]
31. Minimise the number of different parts by using standard components [20, 7]
32. Maximise symmetry in parts and assemblies [8, 7]
33. Plan for large deck spaces to facilitate outfitting [7]
34. Choose bilge radii that allow single plate widths for easier fabrication [4, 9, 6]
35. Use larger frame spacing with thicker plating to reduce number of stiffeners [7]
36. Avoid excessive curvature in stem, bow, and stern; design bulbous bows/sterns for developability [4, 9, 6]

Eliminated guidelines Six guidelines were excluded from further analysis based on the relevance screening. These guidelines primarily prescribe global hull-form characteristics or principal proportions that are typical for commercial or series-built vessels. As such, their application would impose fundamental constraints on aesthetic freedom, hydrodynamic performance, or spatial layout, which are incompatible with the bespoke and aesthetic-driven nature of superyacht design.

1. Maximise flatness of bottom, sides, and decks to reduce plate forming [4, 9, 6]
2. Aim for a high block coefficient to increase flat plating areas [4, 9, 6]
3. Use a small Length-to-Beam (L/B) ratio to minimise frames and reduce steel weight [4, 9, 6]
4. Favour large flat bottoms; avoid unnecessary rise-of-floor amidships [4, 9, 6]
5. Keep stems and transoms straight; avoid complex cruiser sterns or cambered transoms [4, 9, 6]
6. Design a long parallel mid-body to maximise repeated parts and simplify block geometry [4, 9, 6]

The preceding sections have reviewed both established Design for Production guidelines in shipbuilding practice and state-of-the-art research on cost assessment, complexity metrics, and Design for X methodologies. Collectively, these contributions provide valuable insights into how design decisions influence production effort and cost. However, they differ substantially in scope, level of validation, and contextual applicability.

While some approaches offer qualitative guidance for improving producibility, others provide quantitative mechanisms to relate geometry and structural characteristics to production effort. Yet, their integration remains limited, particularly in the context of highly customised, one-off superyacht hull construction.

The following discussion therefore critically synthesises these strands of literature, contrasts their respective strengths and limitations, and reflects on their combined implications for production-oriented early-stage structural design in bespoke superyacht projects.

2.3.3. Discussion

The reviewed applications and principles differ substantially in scope, level of detail, and intended domain of application. This discussion contrasts their respective strengths and limitations, highlights complementarities and tensions between Design for X approaches and cost assessment methods, and reflects on their implications for one-off superyacht hull construction.

Design for X

The reviewed literature demonstrates that Design for X (DfX) provides valuable mechanisms to relate design decisions to producibility and cost. Methods addressing modularity, design simplification, Design for Manufacturing (DfM) prioritisation, Lean-based DfX frameworks, and simplified Design for Assembly (DfA) have shown potential to improve production efficiency in various industrial contexts. However, their direct applicability to bespoke superyacht construction remains limited.

Several studies emphasise producibility-oriented design rules as key cost drivers. Bertram's hull design method [4] illustrates how surface curvature directly influences forming and straightening effort, while Moeeni's IAR analysis [20] highlights the importance of reducing part count, fasteners, and unnecessary complexity. These findings suggest that simplification and curvature management are powerful levers for cost reduction. At the same time, these approaches have not been validated in the superyacht domain, where aesthetic freedom and client-driven design requirements often outweigh producibility considerations. As a result, DfM-oriented methods require adaptation to contexts where design freedom is intentionally preserved while production efficiency remains critical.

More comprehensive DfX frameworks aim to integrate multiple disciplines early in the design process. Lean-based approaches, such as the framework proposed by Dombrowski, Schmidt, and Schmidtchen [12], provide structured ways to manage trade-offs between competing lifecycle objectives, while simplified, team-based DfA methods [21] demonstrate how cross-functional collaboration can reveal assembly inefficiencies. Although these frameworks show promise in manufacturing environments, they remain largely unvalidated in large-scale, highly customised shipbuilding projects. Their effectiveness and transferability to superyacht hull construction therefore remain uncertain.

Quantitative approaches offer additional insight into the relationship between design complexity and producibility. Structural complexity metrics proposed by Caprace and Rigo [8] provide a means to identify cost-intensive design features and complexity "hotspots". For superyachts, however, complexity is often a deliberate design choice linked to aesthetics or functionality. This highlights the need for approaches that can distinguish between value-adding complexity and complexity that primarily increases production effort without contributing to design intent.

Overall, the literature indicates that while DfX principles are conceptually applicable to superyacht construction, they require contextual adaptation, quantitative support, and validation to address the unique balance between aesthetics, quality, and producibility inherent to bespoke yacht projects.

Cost assessment

The reviewed cost assessment methods provide complementary perspectives on how design decisions influence production cost, yet most have been developed for general or serial shipbuilding contexts. Their application to one-off superyacht construction is challenged by high levels of customisation, limited availability of detailed cost data, and the dominant role of aesthetics.

Bertram's combined top-down and bottom-up costing approach [4] demonstrates how global hull parameters and local geometric characteristics can be linked to production effort. By identifying curvature-related cost drivers early, the method supports informed trade-offs between hydrodynamic performance and producibility. In superyacht projects, however, such curvature issues are often identified late in the design process, limiting the scope for major design changes. Earlier application of similar analyses could still enable mitigation of smaller, yet costly, producibility issues.

Feature-Based Costing (FBC), as developed by Caprace [7], offers a structured framework that links CAD/CAM-derived features to production cost through the Ship Work Breakdown Structure. Its main strength lies in providing traceable and iterative cost feedback during early design phases. However, its effectiveness depends strongly on the availability of detailed production data and reliable man-hour norms, which are often lacking in bespoke superyacht construction. Without such data, cost estimates tend to rely on aggregated norms, reducing accuracy. Integrating FBC with additional indicators that capture structural complexity could improve its robustness in this context.

Caprace's fuzzy straightening metric further addresses uncertainty in estimating production effort by incorporating expert knowledge and probabilistic modelling [7]. This is particularly relevant for superyachts, where thin plating and high surface quality requirements increase straightening effort. While the method provides more realistic estimates, it also introduces modelling complexity and requires continuous calibration with yard-specific data.

Structural complexity metrics [8] add a complementary dimension by quantifying shape, assembly, and material complexity and linking these measures to observed production effort. For one-off superyachts, such metrics could support early identification of costly design features. However, their practical use requires yard-specific calibration and careful interpretation to avoid overemphasising numerical scores at the expense of design intent.

In summary, existing cost assessment methods provide valuable tools for relating design to production cost, but none are directly tailored to the bespoke nature of superyacht construction. Key challenges include limited data availability, integration with highly customised design processes, and the need to differentiate between aesthetic complexity and unnecessary cost drivers.

2.3.4. Research opportunities

Despite substantial progress in Design for X (DfX) methodologies and production-oriented cost assessment, the literature reveals several unresolved challenges when these approaches are applied to one-off steel superyacht hull construction. These challenges stem primarily from the highly customised, aesthetic-driven nature of superyachts, which fundamentally distinguishes them from serial or commercially oriented shipbuilding. The following research gaps are identified as particularly relevant for advancing production-oriented design decision-making in this context.

Research gaps identified from literature

1. Absence of a holistic cost assessment perspective for one-off superyacht hulls. Existing approaches, including curvature-based costing [4], Feature-Based Costing and fuzzy straightening models [7], and related activity- or feature-oriented methods, each address specific cost drivers. However, these methods are typically developed in isolation and for general or serial shipbuilding contexts. The literature does not provide a unified perspective that captures how design features, production activities, rework, and structural characteristics interact to influence production cost in bespoke superyacht hull construction.

2. Undefined applicability and prioritisation of DfX guidelines for bespoke superyachts. While studies such as Moeeni's IAR analysis [20] demonstrate structured prioritisation of Design for Manufacturing principles, the broader body of DfX guidelines originates largely from general manufacturing or conventional shipbuilding. Their relative importance, feasibility, and relevance remain insufficiently defined for one-off superyachts, where producibility improvements must be carefully balanced against aesthetic intent, client-specific requirements, and high quality standards.

3. Limited validation of DfX frameworks in large-scale yachtbuilding practice. Lean-based DfX frameworks [12] and simplified, team-based Design for Assembly approaches [21] have demonstrated benefits in other industrial sectors by integrating production knowledge early in the design process. However, their applicability and effectiveness in large, highly customised yachtbuilding projects have not been empirically validated. As a result, their practical relevance for superyacht hull construction remains uncertain.

4. Insufficient quantitative insight into the role of structural complexity. Structural complexity metrics [8] and curvature-based analyses [4] establish relationships between design characteristics and production effort. Nevertheless, existing calibrations are primarily based on serial or general shipbuilding. For superyachts, where geometric and structural complexity is often an intentional design choice, the literature lacks quantitative insight into how complexity contributes to production effort and cost, and how value-adding complexity can be distinguished from avoidable cost-driving complexity.

5. Fragmentation between design-oriented and process-oriented improvement approaches. Current research addressing CAD-based cost estimation, producibility-oriented design rules, and process improvement strategies such as Lean remains largely fragmented. The literature does not yet offer a coherent perspective that links early-stage design decisions to downstream production performance, including fabrication effort, rework, and process efficiency, in the context of one-off superyacht hull construction.

6. Limited DfX guidance that explicitly preserves aesthetic intent. Many producibility-oriented design rules, such as simplification, curvature control, and part-count reduction, are recognised as effective cost levers. However, their direct application may conflict with the aesthetic priorities that define luxury yacht design. The literature provides limited guidance on how DfX principles can be adapted to explicitly preserve aesthetic intent while still reducing production effort and structural complexity.

2.4. Conclusion of the Literature Review and Research Positioning

This literature review demonstrates that, although a wide range of cost assessment methods and Design for X (DfX) principles is available, none fully address the requirements of highly customised, one-off steel superyacht hull construction in an integrated an context-specific manner.

Existing cost estimation approaches, including both top-down and bottom-up methods, capture individual aspects of production effort, but typically fail to represent the combined influence of design complexity, assembly effort, rework and execution-related variability during early design stages. As a result, cost predictability remains limited in bespoke superyacht projects, where production characteristics differ fundamentally from those of series-built or standardised vessels.

The literature on Design for X provides extensive qualitative guidance for improving producibility, assembly and manufacturing performance. However, these principles are generally developed for generic shipbuilding or manufacturing contexts and are not systematically prioritised for the specific characteristics of superyacht construction. Moreover, their application is often qualitative in nature and rarely translated into quantifiable design parameters that can be evaluated within an early-stage structural design context.

Several studies have demonstrated that production-oriented indicators, such as complexity metrics and sustainability-related measures, can be quantified and correlated with manufacturing effort. Nevertheless, the literature lacks an integrated framework that combines qualitative prioritisation of

Design for Production principles with subsequent quantitative evaluation of their impact on structural design, production cost and related performance indicators. Existing approaches tend to address these aspects in isolation, without explicitly linking early-stage design measures to their economic and structural consequences.

Taken together, these findings identify a clear research gap. There is a need for a structured approach that first identifies and prioritises Design for Production guidelines that are most relevant to one-off superyacht hull construction, and subsequently translates these guidelines into measurable design variables suitable for quantitative evaluation. Such an approach should enable the systematic assessment of the effects of production- oriented design measures on cost, complexity and sustainability-related performance, while remaining compatible with the bespoke and aesthetic-driven nature of superyacht design. Addressing this gap forms the basis for the research approach adopted in the subsequent chapters of this thesis.

3

Methodology

This chapter describes the methodological approach that will be used to study design-oriented Design for Production (DfP) measures in one-off superyacht (steel) hull construction. The approach combines qualitative expert input with quantitative structural and cost modelling, with the objective of translating production-oriented guidelines into quantifiable parameters suitable for early-stage engineering evaluation. As demonstrated in Chapter 2, existing DfX methodologies and cost assessment approaches remain fragmented and insufficiently tailored to the bespoke, aesthetic-driven nature of superyacht hull construction, highlighting the need for an integrated and context-specific evaluation framework.

Within the context of one-off construction, the primary objective of this methodology is to develop systematic insight into how individual design choices influence production cost, structural performance, and manufacturability. Rather than identifying a single optimal solution, the methodology is intended to support informed decision-making by enabling structured comparison between alternative design strategies.

The chapter is structured into two main phases. The first phase focuses on the assessment, elimination and prioritisation of the DfP guidelines identified in the literature review. Although Chapter 2 resulted in an extensive list of potentially relevant principles, their relative importance and applicability to bespoke superyacht hull construction require further evaluation. This phase therefore applies structured assessment methods and expert judgement to refine the broad inventory into a focused subset of design-oriented guidelines suitable for quantitative analysis.

The second phase outlines the quantitative approach. In this phase, qualitatively prioritised guidelines will be translated into measurable design characteristics and evaluated using a set of production-oriented Key Performance Indicators (KPIs). These KPIs are structured to support early-stage design decision-making by enabling comparison of alternative design solutions. A Feature-Based Costing (FBC) model will subsequently be applied to assess the production cost implications associated with the evaluated Design for Production measures.

Together, these methodological elements form a structured research workflow that links high-level production-oriented design principles to detailed engineering assessment. This workflow is intended to support consistent and comparable evaluation of Design for Production guidelines, enabling their assessment not only in theoretical terms, but also with respect to practical implications for production efficiency and structural safety in one-off superyacht hull construction.

3.1. Overview of Research Approach

The research methodology is structured in two interconnected phases. The first phase focuses on the qualitative evaluation and prioritisation of Design for Production (DfP) guidelines relevant to one-off superyacht hull construction. Expert judgement is applied to identify which guidelines are most applicable within this context.

In the second phase, the selected guidelines are translated into measurable design variables. These variables are subsequently evaluated through structural analysis, cost estimation, and optimisation in order to assess their technical and economic impact.

1. **Qualitative analysis:** prioritisation and categorisation of relevant DfP guidelines.
2. **Quantitative analysis:** assessment of the structural and economic effects of the selected design measures.

This section describes the complete research methodology, clarifies the interaction between both phases, and outlines the procedures and data exchange that structure the remainder of this chapter.

3.1.1. Qualitative phase: assessment and prioritization of DfP guidelines

The qualitative stage was conducted through a structured literature review, resulting in a set of 36 DfP guidelines. These guidelines reflect decades of accumulated knowledge and practical experience in production-oriented shipbuilding. However, the vast majority were originally developed for series-built vessels such as bulk carriers, cargo ships, and passenger or cruise ships. Their direct applicability to large, custom-built, one-off superyachts therefore cannot be assumed.

To address this limitation, expert judgement is applied to assess the specific relevance of each guideline within the context of one-off superyacht hull construction. An initial screening selects the guidelines considered suitable for further evaluation. The shortlisted guidelines are subsequently assessed using a structured IAR (Importance–Applicability–Reduction) framework, derived from the Design for Manufacturing approach of Moeeni, Javadi, and Raissi [20]. This framework enables a consistent comparison and ranking of the guidelines based on their perceived impact and practical feasibility.

At the start of the second phase, it was subsequently decided to concentrate further on *design-oriented* DfP guidelines. Choosing this direction is for two reasons. First of all, a parallel internal research project of the same company, had focused on process-oriented production improvements, leaving process-oriented production improvements beyond the scope of this study. Second, the focus of research turned towards *reduced design complexity*, with an emphasis on structural simplicity and parts number reduction in particular. For manufacturing cost and manufacturability, these aspects are directly measurable. Consequently, process-oriented guidelines will be assigned to the parallel study project and only the design-oriented guidelines used for the process are considered.

3.1.2. Quantitative phase: cost-based KPI evaluation of design-oriented DfP measures

The quantitative part consists of converting the chosen design-oriented DfP guidelines into the analysable design variables and the impact that these design variables have on both structural performance and fabrication cost is examined. This evaluation is conducted within the context of three interrelated modelling elements:

1. the development of a Feature-Based Costing (FBC) model capable of estimating fabrication cost relations and evaluating KPIs based on the structural characteristics of individual components, grounded in yard and design practice;
2. the development of an integrated structural and cost optimisation framework for the systematic generation of structurally feasible and cost-efficient design configurations, In the context of this study, the term "optimisation" refers to a structured and systematic exploration of a discrete, rule-constrained design space in order to identify structurally admissible and production-relevant configurations. It does not imply continuous mathematical optimisation or the search for a global cost minimum.;
3. the definition of a structural feasibility space that must be satisfied by all potential design configurations with respect to buildability, weight, and quality.

Quantitative and qualitative phases provide a unified research methodology, the first moving from the lowest conceptual level of the DfP principles to structural analysis and the latter to cost quantification. This approach allows for the search of suitable design configurations to facilitate production efficiency with respect to one-off superyacht hull building. The full flow-through and outputs of each phase are shown in Fig. 3.1.

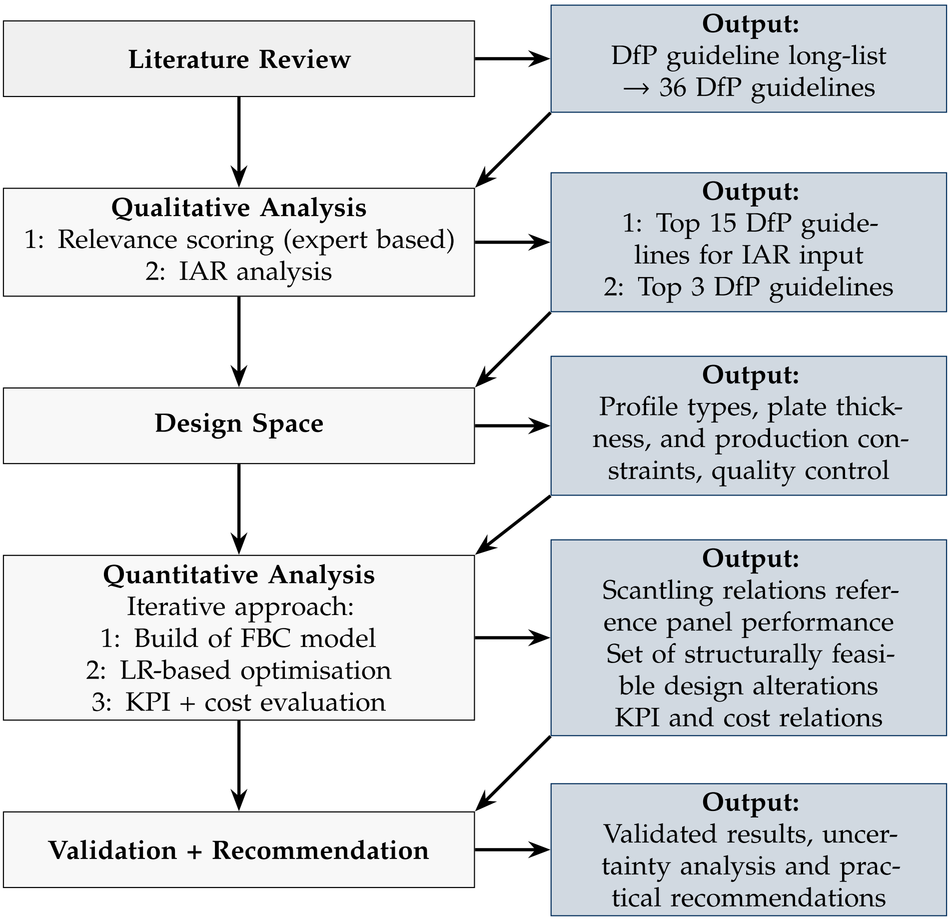


Figure 3.1: Overview of the research methodology with corresponding outputs per phase.

Although Chapter 2 identified a broad set of Design for Production guidelines relevant to shipbuilding, it did not yet determine which of these are most applicable to bespoke superyacht hull construction, nor how their impact could be quantified. Therefore, a structured two-phase methodology is required: first to prioritise and contextualise the guidelines, and subsequently to translate them into measurable design variables suitable for engineering evaluation.

3.2. Evaluation and Prioritisation of Design for Production Guidelines

While the literature review provided an extensive inventory of Design for Production guidelines, directly translating all identified principles into quantitative evaluation would be impractical and methodologically inconsistent. A prioritisation step is therefore required to focus subsequent analysis on the most relevant and impactful design-oriented measures within the context of one-off superyacht construction.

This section details the qualitative procedure used to filter and prioritise the DfP guidelines prior to quantitative evaluation. First it elaborates on how the selection of the guidelines is conducted, followed by the prioritisation of the guidelines. Expert knowledge is used to assess each guideline according to three criteria: *Importance*, *Applicability*, and *Reduction potential* (IAR), following the framework proposed by Moeeni, Javadi, and Raissi [20].

3.2.1. DfP guideline selection

The initial guideline set was derived from academic literature and expert input. To ensure practical relevance, the full list was reviewed through expert interviews conducted at Shipyard Slob and De

Voogt Naval Architects (DVNA). The professional backgrounds of the interviewed experts are presented in Table 3.1.

Table 3.1: Professional background of interviewed experts.

Role	Number of Experts
Manager Engineering	1
Structural Engineer (DVNA)	1
Head of R&D (DVNA)	1
Project Engineer	2
Head of Work Preparation	2
Head of Metal Work (Assembly)	1

Each guideline was scored on a scale from 0 to 5 based on its perceived relevance. If a guideline fell outside the expertise of a particular expert, it was excluded from their assessment and labelled “-”. The results of the selection are presented in the list below. The full scoring can be found in Table **??** of Appendix **??**. This procedure ensured that only guidelines compatible with the fully customised superyacht production were retained. The outcome of this step was a shortlist of 15 guidelines for further qualitative evaluation.

1. Avoid overly thin plates that cause distortion and rework to reduce construction/production costs.
2. Plan the outfitting sequence early to minimise congestion and reduce construction/production costs.
3. Favour single curvature or developable surfaces to reduce construction/production costs.
4. Form multidisciplinary teams of design, production, and outfitting specialists to align decisions and reduce construction/production costs.
5. Use larger frame spacing with thicker plating to reduce the number of stiffeners and construction/production costs.
6. Apply work breakdown structures (system-, procurement-, and production-oriented) to better organise production activities and reduce construction/production costs.
7. Design for maximum use of high-productivity tools (e.g., automatic/robot welding, cutting, scanning, 3D metal or plastic printing) to reduce construction/production costs.
8. Make (greater) use of feedback loops between production and design teams to improve manufacturability and reduce construction/production costs.
9. Use straight frames, floors aligned with main frame lines, and/or straight internal structures to reduce construction/production costs.
10. Simplify local panel curvature to create simpler forms and reduce construction/production costs.
11. Plan piping, cable routes, and straight pipe runs (earlier) for easier pre-outfitting and reduced construction/production costs.
12. Prefer assembly in open spaces over confined areas (e.g., increase block size to avoid work in double bottoms) to reduce construction/production costs.
13. Ensure good accessibility and visibility during assembly to reduce construction/production costs.
14. Where possible, separate aesthetic forms from the load-bearing structure, applying add-ons and new production techniques to improve manufacturability and reduce construction/production costs.
15. Use pre-stressing in plates to prevent distortion and reduce construction/production costs.

3.2.2. IAR guideline assessment

Following the literature review, the shortlisted guidelines were evaluated using the IAR framework, which enables a structured comparison of their expected relevance, feasibility and cost reduction potential. In this study the method is applied as an expert-elicitation tool, extended with an additional

Confidence factor to account for differences in respondent expertise. The four criteria are defined as follows:

Importance – the urgency or significance of addressing the issue targeted by the guideline;

Applicability – the extent to which the guideline can be realistically implemented within the one-off construction context;

Reduction potential – the expected ability of the guideline to reduce production cost and/or structural complexity;

Confidence – how certain the participant is about the answers provided for the guideline.

Based on these four criteria, a structured scoring procedure is required to quantify expert judgments in a consistent manner. The scoring method used in this study is outlined below.

Scoring method IAR

The IAR scoring method uses a seven-point scale (0–6) for each criterion, where 0 represents a negligible contribution, 5 represents a high contribution, and 6 indicates that the respondent could not provide an answer. To ensure that the responses reflect the expertise of each participant, a confidence factor is included. After evaluating each guideline, participants specify their level of knowledge regarding the topic, which is subsequently used as a multiplier in the final IAR(C) score. The individual scoring rubric is shown in Table 3.2.

Table 3.2: IAR(C) scoring rubric for DfP guidelines.

Score	Importance	Applicability	Reduction Pot.	Confidence
0	Not important	Not applicable	<2%	-
1	Slightly important	Slightly applicable	2–5%	Very low
2	Moderately important	Moderately applicable	5–10%	Low
3	Important	Applicable	15–20%	Medium
4	Very important	Very applicable	20–30%	High
5	Almost critical	Critical to apply	>30%	Very high
6	N/A or unknown	N/A or unknown	N/A	N/A

To calculate the IAR(C) score of a guideline, an averaging–multiplier method is used. All responses are separated per criterion (I, A, and R). Each individual response is then multiplied by the corresponding confidence factor (C), after which the weighted average for each criterion is computed using Equations (3.2.1) to (3.2.3). Here, n denotes the total number of respondents and i refers to the i-th respondent.

$$I_{\text{avg}} = \frac{\sum_{i=1}^{n} I_i \, C_i}{\sum_{i=1}^{n} C_i} \tag{3.2.1}$$

$$A_{\text{avg}} = \frac{\sum_{i=1}^{n} A_i \, C_i}{\sum_{i=1}^{n} C_i} \tag{3.2.2}$$

$$R_{\text{avg}} = \frac{\sum_{i=1}^{n} R_i \, C_i}{\sum_{i=1}^{n} C_i} \tag{3.2.3}$$

The final IAR score is then obtained using Equation (3.2.4):

$$IAR_{\text{avg}} = I_{\text{avg}} \, A_{\text{avg}} \, R_{\text{avg}} \tag{3.2.4}$$

Since the IAR assessment constitutes a methodological selection step that directly determines the input for the subsequent quantitative phase, its results are presented in the following subsection as a structured basis for selecting the most relevant design-oriented DfP guidelines.

3.2.3. Prioritised DfP guidelines — IAR results

This section presents the outcomes of the IAR(C) analysis used to prioritise the Design for Production (DfP) guidelines for quantitative evaluation. Figure 3.2 illustrates the scope of the survey and the distribution of participants across departments.

A total of 30 responses were collected, representing 15 organisational departments. This wide spread indicates that the analysis integrates perspectives from a broad range of professional domains, supporting the validity of the prioritisation. The Engineering department accounts for the largest share of respondents, followed by project-oriented and production-support functions such as project management, work preparation, procurement and construction coordination.

This diversity ensures that the prioritised guidelines reflect expertise across multiple stages of the yacht-building process, including design, structural engineering, procurement, production and facility management. Such cross-sectional engagement strengthens confidence that the prioritisation captures both technical and organisational considerations.

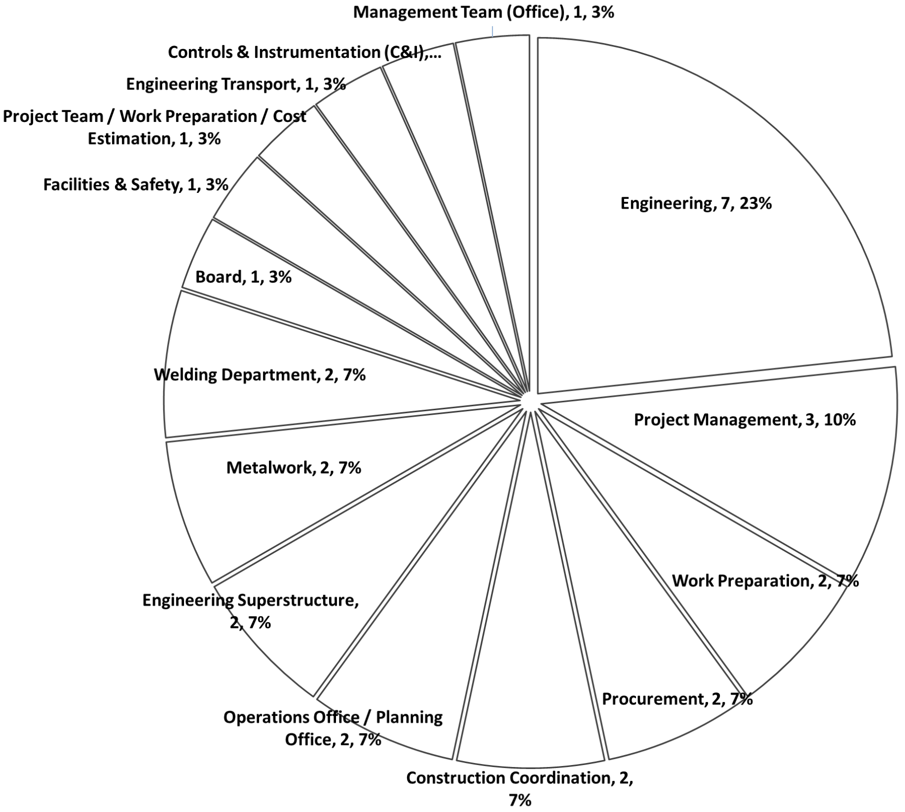


Figure 3.2: Distribution of the 30 questionnaire responses across 16 departments involved in superyacht hull design and production. The size of the "pie" pieces indicate the amount respondents from a given department, which affects the weighting of expert judgement in the subsequent IAR analysis.

As described in Section 3, respondents evaluated each guideline according to three criteria: Importance, Applicability and expected Reduction potential. The following subsections discuss the results per criterion before presenting the aggregated IAR ranking.

Interpretation of results per criterion

The IAR(C) framework combines three indicators: the perceived Importance (I) of a guideline, its Applicability (A) in current practice and its hypothesised Reduction potential (R). The results are discussed below.

Importance The Importance scores indicate a strong emphasis on structural reliability and assembly quality. High scores for assembly accessibility (4.53) and the use of straight, standardised structural arrangements (4.35) confirm that measures aimed at reducing rework and improving alignment are prioritised. The guideline "Avoid overly thin plates that cause distortion and rework" received the second highest value (4.47), showing that respondents regard distortion control and plate stiffness as primary contributors to fabrication efficiency.

Guidelines that intervene directly in hull geometry, such as developable surfaces (3.78) and simplified panel curvature (3.73), score lower. This reflects a familiar trade-off within yacht construction between geometric freedom, aesthetic requirements and production efficiency.

Separating aesthetic forms from load bearing structure (3.48) also scores lower than most guidelines on importance, which indicates they are not deemed the biggest problem in the production process. Increasing scantlings (3.13) is seen as the least important factor to address. This can be due to the standardisation efforts that have been done regarding the scantlings over the last years.

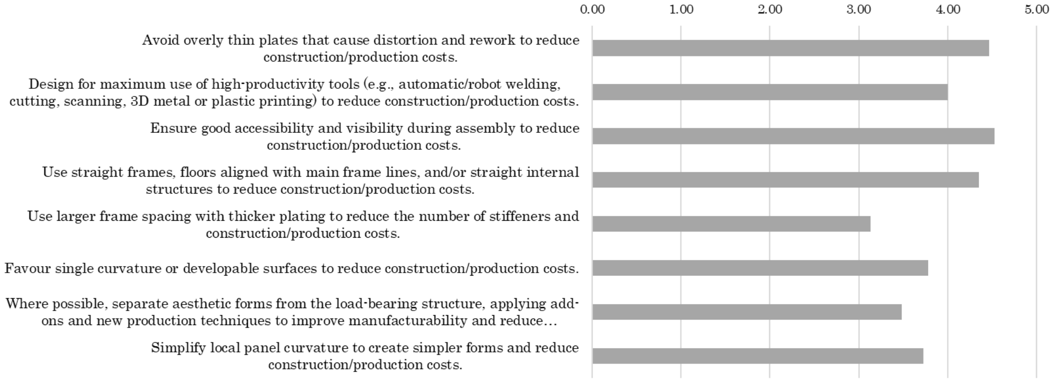


Figure 3.3: Importance scores assigned by 34 respondents for eight Design-for-Production guidelines on a 1–5 scale, where higher values indicate a greater perceived contribution to production efficiency. Structural-quality measures score highest, while geometry-constraining measures score lowest.

Applicability Applicability captures whether a guideline can feasibly be introduced within current engineering and production practice. Accessibility during assembly (3.90) and the use of high-productivity manufacturing tools (3.39) rank high (1 and 3 respectively), suggesting compatibility with existing workflows. Thin-plate avoidance again scores high (3.66), as this guideline requires minimal procedural change. Lower Applicability values are associated with geometric simplifications. Developable surfaces (2.62) and simplified curvature (2.33) appear constrained by styling expectations, classification limits or owner-driven aesthetics. The moderate score for larger frame spacing with thicker plating (2.79) indicates reservations, due to having a greater impact on the ship's performance.

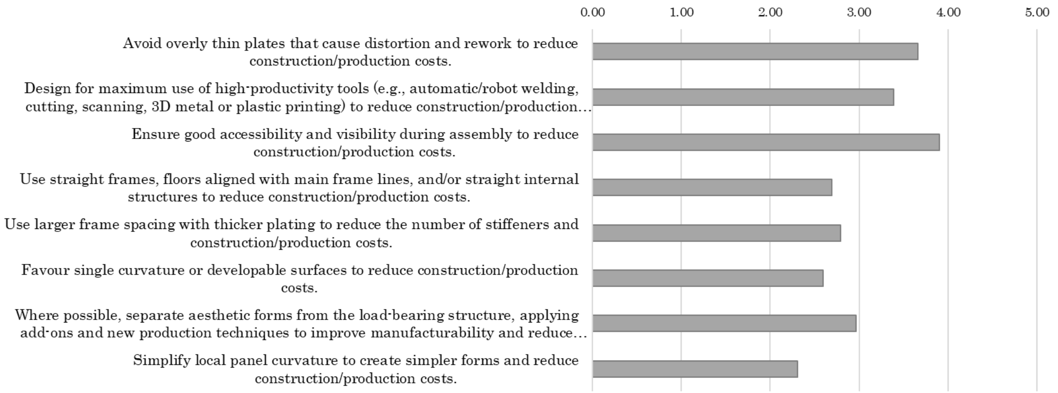


Figure 3.4: Applicability scores assigned by 34 respondents for eight DfP guidelines, indicating the perceived ease of implementation in current superyacht design practice. Higher values represent fewer procedural or regulatory barriers. Geometry-altering guidelines display the lowest applicability.

Reduction potential The expected Reduction values remain relatively modest, which is consistent with cautious expert judgement during early-stage estimations. The highest percentage (9.26%) is assigned to the use of larger frame spacing and thicker plating. This is unexpected, as it was deemed less important than other design guidelines. Thin-plate avoidance follows at 8.88%, reflecting a belief that both distortion mitigation will reduce rework. The top three is closed by adoption of high-productivity tools, indicating anticipated labour reductions through automation or digitalised fabrication.

Most other measures fall in the range of 6%<R<8%, suggesting a lower perceived effect on cost. This reinforces that production costs arise from interactions between multiple design decisions rather than from isolated measures.

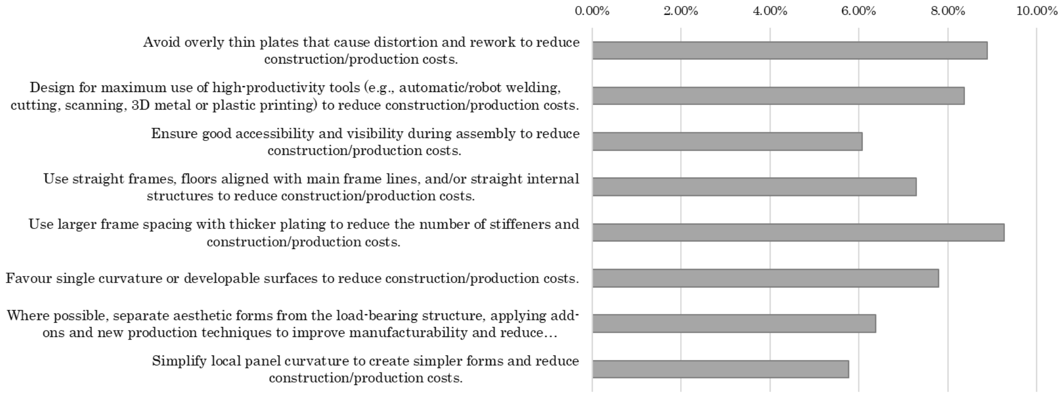


Figure 3.5: Expected Reduction potential for eight DfP guidelines, expressed as percentage labour-reduction estimates based on expert judgement by 34 respondents. Values range between 7% and 11%, indicating cautious expectations for single-measure cost savings.

Final IAR ranking The final IAR values reflect the combined effect of the three evaluation criteria. *Avoiding thin plates* ranks first (IAR = 1.45), benefiting from high scores in both *Importance* and *Applicability*. This is followed by *increased use of high-productivity tools* (IAR = 1.13), which combines strong perceived cost-reduction potential with feasible implementation. *Accessibility and visibility during assembly* ranks third (IAR = 1.07), completing the group of top-ranked guidelines.

What these guidelines have in common is that they are implemented during the design phase while primarily affecting the production process. They focus on reducing labour costs rather than reducing the number of parts or overall product complexity.

Structural optimisation guidelines occupy mid-range positions in the ranking. *The use of straight frames and alignment of scantlings* ranks fourth (IAR = 0.85), followed closely by *larger frame spacings* (IAR = 0.81). This indicates that interventions in structural design are less favoured than process-oriented improvements, yet are still preferred over measures that affect aesthetic design.

A noticeable decline in IAR values is observed in the lower-ranked positions. Hull-geometry interventions, including *developable surfaces* (IAR = 0.77) and *simplified curvature* (IAR = 0.50), appear near the bottom of the ranking, highlighting the persistent tension between aesthetic freedom and production simplification. Similarly, the guideline promoting *separation of aesthetic and structural functions* (IAR = 0.66) reinforces this trend.

Overall, the ranking suggests a clear preference for measures that improve manufacturability without constraining exterior styling. It further underscores the perception that the adoption of production technologies is a key enabler of cost reduction in one-off steel yacht construction.

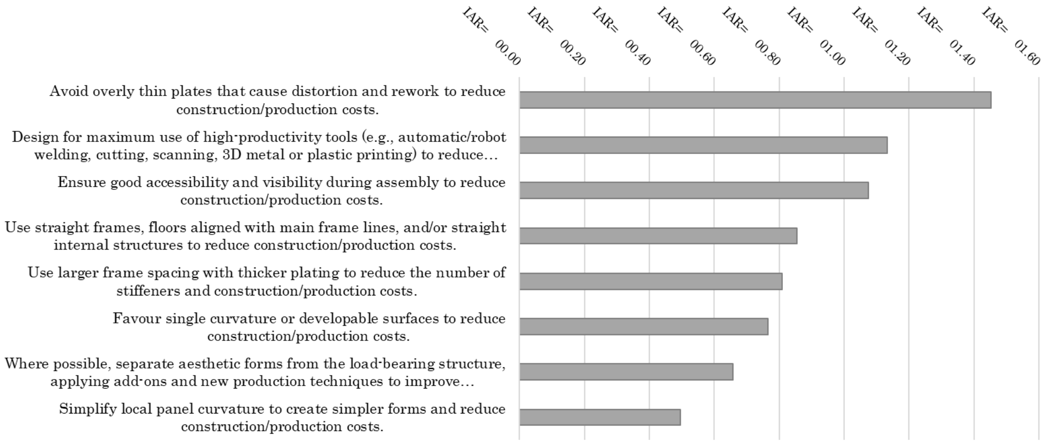


Figure 3.6: Aggregated IAR values for eight DfP guidelines, combining Importance (1–5), Applicability (1–5) and expected Reduction potential (0–1) into a single prioritisation measure. Higher scores indicate stronger combined relevance to production cost reduction. Results show that structural distortion control dominates, while hull-form interventions score lowest.

Selection of guidelines for quantitative modelling

The IAR(C) prioritisation provides a structured indication of which Design-for-Production (DfP) guidelines are considered most relevant across the organisation. However, the final selection of measures for quantitative modelling reflects not only the ranking outcomes, but also the strategic priorities expressed by Scheepswerf Slob and the requirements imposed by parametric cost modelling.

During discussions with the shipyard, reduction of part count and simplification of structural complexity were identified as the preferred starting point for design-oriented optimisation. Rather than focusing on downstream process interventions, the yard emphasised measures that directly influence the geometry, subdivision and continuity of the primary steel structure. These measures are considered to offer the greatest potential for cost reduction in one-off steel yacht construction, as they affect fabrication effort, weld length, alignment tolerance and distortion behaviour at source.

For this reason, the quantitative phase concentrates on guidelines that reduce the number of structural members, rationalise framing arrangements and limit geometric discontinuities. These include the avoidance of excessively thin plates to control welding distortion, the alignment and straightening of internal members, and—most prominently—the use of larger frame spacing in combination with increased plate thickness. While the latter guideline did not achieve a top position in the combined IAR ranking, it directly targets part-count reduction by decreasing the number of stiffeners and intermediate members. Moreover, it interacts strongly with two of the highest-ranked IAR criteria: distortion control and structural regularity.

The selection therefore balances expert judgement with yard requirements. High-scoring IAR guidelines provide boundary conditions and qualitative priorities, while the frame-spacing concept offers a clearly defined geometric variable suitable for quantitative modelling. The resulting set of DfP principles is summarised in Table 3.5, structured according to design domain and intervention strategy.

	Simplifying design – reducing number of parts	**Improving process**
Structural Design	• Avoid overly thin plates to limit distortion and rework. • Use straight frames and aligned internal members. • Increase frame spacing combined with thicker plating to reduce stiffener count.	• Avoid overly thin plates to limit distortion and rework. • Ensure good accessibility and visibility during assembly. • Enable the use of high-productivity tools (e.g. automated welding and cutting).
Aesthetic Design	• Separate aesthetic forms from load-bearing structure where possible. • Favour developable or single-curvature surfaces. • Simplify local panel curvature.	• Enable the use of high-productivity tools in aesthetic components.

Table 3.5: DfP guideline matrix split by design domain (structural vs. aesthetic) and intervention strategy (simplifying design vs. improving process).

The guideline matrix introduces a second layer of organisation beyond the numerical IAR(C) prioritisation. The vertical axis distinguishes between *structural design*, affecting scantlings, framing layout and welding behaviour, and *aesthetic design*, influencing curvature, surface development and exterior styling. This distinction reflects the dual nature of superyacht hull design, where production efficiency is constrained by visual requirements and owner expectations.

The horizontal axis differentiates between guidelines that simplify the design by reducing the number of parts and those that improve production efficiency without altering the structural topology. The upper-left quadrant, containing structural design measures aimed at part-count reduction, forms the primary focus of the quantitative analysis. These measures define parametric design variables such as frame spacing, stiffener density and plate thickness that can be evaluated consistently within a cost-based optimisation framework.

Consequently, the quantitative phase of this research concentrates on scantling optimisation as a means of reducing part count while maintaining acceptable distortion behaviour, structural performance and manufacturability. Non-structural guidelines are not explicitly included in the optimisation model, but are retained as qualitative checks when interpreting the results, ensuring compatibility with yard practices and quality standards.

In summary, the qualitative phase narrows the broad set of DfP guidelines to a focused group of design-oriented measures that directly influence structural topology and part count. Among these, frame spacing and associated scantling parameters emerge as the most suitable candidates for parametric modelling, as they combine geometric clarity with measurable cost and production implications.

The subsequent section therefore moves from qualitative prioritisation to quantitative evaluation, translating these selected design variables into structural and cost relations that enable systematic assessment of their impact.

3.3. Quantifying Impact of Scantling Configuration on Production Effort and Costs

The prioritised guidelines identified in the qualitative phase indicate which Design for Production principles are considered most relevant. However, their actual influence on structural feasibility, production cost, and complexity remains unknown. A quantitative evaluation is therefore required to assess the measurable consequences of implementing these design-oriented measures.

The objective of the quantitative analysis is to evaluate the cost-saving potential of selected Design-for-Production (DfP) guidelines under realistic shipyard conditions. Each guideline is translated into one or more quantitative relations linking cost and performance, capturing its expected influence on production effort, structural mass, and overall fabrication cost.

Rather than aiming to identify a single mathematically optimal design solution, the purpose of this analysis is to explore the feasible design space and to derive Key Performance Indicator (KPI) relations as a function of the main scantling parameters. These relations are intended to provide transparent insight into the trade-offs between structural requirements, production complexity, and dominant cost drivers.

The resulting KPI relations form a decision-support framework that enables industry practitioners to assess and compare alternative scantling configurations. This supports informed design decisions based on shipyard-relevant constraints, priorities and production considerations. An overview of the KPIs considered in this study is provided in Table 3.6, which also indicates which criterion is evaluated quantitatively or which evaluation remains qualitatively.

Table 3.6: Classification of guideline evaluation criteria into quantitative and qualitative categories.

Criterion	Type	Rationale
Primary quantitative engineering KPIs		
Cost	Quantitative	Derived directly from the Feature-Based Costing (FBC) model through feature-level material, fabrication and assembly cost relations
Lead time	Quantitative	Calculated from welding, fabrication and assembly durations relative to a reference panel
Number of parts	Quantitative	Determined directly from the structural layout and scantling configuration
Structural mass	Quantitative	Computed from part geometry, plate thickness and stiffener dimensions
Sustainability	Quantitative	Estimated from steel production emissions, welding-related energy use and structural mass
Production feasibility		
Impact on process	Qualitative	Reflects influence on production workflow, informed by trends in quantitative KPIs
Knowledge maturity	Qualitative	Indicates yard familiarity and implementation readiness of the proposed design measure
Strategic or perception-related factors		
Quality	Qualitative	Relates to buildability, production tolerances and technical perception, governed by quantitative KPIs
Brand image	Qualitative	Relates to aesthetic perception and brand identity, outside the scope of structural and cost modelling

Quantitive KPI Definition

To evaluate and compare the structural panel configurations resulting from the optimisation study, a set of analysis criteria is defined. These criteria are selected to represent the dominant cost drivers and performance indicators relevant to the fabrication of one-off steel hull structures, with a particular emphasis on production-oriented design aspects. Together, they enable a consistent and structured comparison between conventional reference designs and optimised alternatives.

Part count evaluation Part count is considered one of the most influential indicators from a Design for Production perspective. It directly reflects the structural complexity of a panel and has a cascading impact on multiple stages of the fabrication process. An increased number of parts typically leads to longer weld lengths, a higher number of assembly operations, and greater handling and alignment effort. As a result, part count reduction contributes not only to lower welding and handling costs, but also to reduced assembly time and overall production lead time. For this reason, minimising part count is regarded as a primary objective in simplifying production processes and reducing total fabrication cost. Among the selected KPIs, part count is considered the dominant driver, as it directly propagates into welding effort, assembly time, lead time, and overall fabrication cost.

Mass evaluation Structural mass is evaluated relative to the reference panel configurations currently used by the shipyard. Although mass is not a direct cost driver on its own, it strongly correlates with material costs, transport effort, and environmental impact. In addition, excessive mass may indicate inefficient structural solutions. To ensure practical relevance and feasibility, a maximum allowable mass increase of 25% relative to the reference configuration is imposed as a constraint in the evaluation.

Production time evaluation Production time is used as a proxy for fabrication lead time and is closely related to both part count and welding effort. Reductions in production time may enable faster project delivery or help alleviate bottlenecks in critical production stages, assuming a constant workforce. The evaluation of production time therefore provides insight into the manufacturability and scheduling implications associated with different panel configurations.

CO_2 emissions evaluation The evaluation of CO_2 emissions is included to assess the environmental impact of the considered structural design choices. Emissions are primarily driven by material usage and fabrication effort and are therefore closely linked to structural mass and production activities. This criterion enables a comparison of optimised designs not only in terms of economic performance, but also with respect to sustainability-related considerations.

Cost evaluation Cost evaluation is performed to identify the dominant cost drivers within the structural panels and to quantify the potential cost reductions achieved through optimisation. Contributions from material, welding, metalwork, transport, and assembly activities are considered in order to obtain a comprehensive understanding of fabrication cost behaviour. This criterion forms the primary basis for identifying cost-efficient design solutions and supporting production-oriented design decisions.

Overall, the selected analysis criteria capture the key technical, economic, and environmental aspects of steel hull fabrication and form the basis for a multidimensional comparison between reference and optimised panel configurations.

Treatment of interior spacing, global ship dimensions and gross tonnage Within the quantitative analysis, interior space is treated as a fixed design constraint. The internal layout and usable volume of the yacht are assumed to remain unchanged. Consequently, increases in stiffener or primary member dimensions cannot be absorbed within the existing structural depth. Instead, they require outward scaling of the hull envelope.

Height-stacking principle

This geometric consequence is implemented through a height-stacking principle. Structural members are organised hierarchically (secondary stiffeners → primary web frames → large girders). An increase at a lower hierarchical level propagates upward to the higher structural levels.

Let Δh_s denote the increase in secondary stiffener height.

The corresponding increase in primary member height is defined as:

$$\Delta h_p = \alpha \, \Delta h_s \tag{3.3.1}$$

where α represents the amplification factor between secondary and primary structural levels. For standard primary members, $\alpha = 2$ is assumed.

If an additional hierarchical level is present (e.g. deep web frames or longitudinal girders), the increase propagates further:

$$\Delta h_g = \beta \, \Delta h_p \tag{3.3.2}$$

where β represents the amplification factor between primary members and large girders. When such members are present, $\beta = 2$ is adopted.

The total vertical increase due to height stacking over N structural levels is expressed as:

$$\Delta H = N \, \Delta h_{\text{max}} \tag{3.3.3}$$

where Δh_{max} is the governing height increase of the highest structural level in the hierarchy.

Propagation to global dimensions

To maintain geometric consistency, principal hull proportions are assumed constant:

$$\frac{L_1}{B_1} = \frac{L_2}{B_2} \qquad \text{and} \qquad \frac{B_1}{T_1} = \frac{B_2}{T_2} \tag{3.3.4}$$

As a result, an increase in structural height ΔH propagates proportionally to the other principal dimensions. The updated global dimensions (L_2, B_2, T_2) therefore scale consistently with the original vessel proportions.

Role in the optimisation framework

Global dimensions and gross tonnage are treated as dependent variables resulting from local scantling decisions. They are not directly optimised. Instead, their influence is incorporated implicitly through associated changes in structural mass, material consumption, weld length, production effort, CO_2 emissions, and total production cost.

The analysis does not consider commercial consequences of increased gross tonnage, resale value, or market positioning of a larger vessel. Only the production-related implications of geometric growth are evaluated.

By treating global dimensions as dependent outcomes rather than optimisation objectives, the model remains focused on panel-level Design for Production decisions while still capturing the structural and fabrication consequences of height stacking.

3.3.1. Quantitative research approach

Although the quantitative phase is presented as a structured workflow, the analysis is inherently iterative. The modelling steps form an interdependent process in which each stage provides essential input to the next. This separation balances modelling fidelity, computational efficiency, and practical applicability, enabling large-scale design exploration without relying on a single fully integrated high-fidelity model.

Prior to modelling, a unified global feasibility space is defined (Section 3.3.2). This space constrains the exploration to discrete panel configurations that are geometrically plausible and compatible with shipyard practice (e.g. standard profile and plate availability and handling limits).

Production-feasibility indicators that depend on fabrication modelling, most notably welding-induced distortion risk, are introduced after the costing framework has been defined and are applied as post-processing filters.

1. Global feasibility space and yard constraints First, a discrete feasibility space is defined, including the adopted stiffened-panel abstraction, parameter ranges, and practical shipyard constraints (e.g. commercially available plates and HP profiles, and handling limits).

2. Feature-Based Costing (FBC) model development Second, an Excel-based Feature-Based Costing (FBC) model is developed to quantify panel-level KPIs and to calibrate cost and production relations using reference configurations representative of current Slob practice. This step also defines the fabrication-related quantities required for subsequent production-feasibility assessment (e.g. weld length, heat input proxies, and bending-stiffness indicators).

3. LR-based optimisation (concept generation) Third, a Lloyd's Register pressure-envelope based optimisation is performed in Matlab. Within the predefined feasibility space, the optimisation generates structurally admissible scantling configurations using calibrated analytical relations. A simplified set of FBC-derived relations is used as surrogate objective functions to efficiently identify cost-efficient regions of the discrete design space.

4. Post-optimisation feasibility screening and full FBC re-evaluation Finally, candidate configurations are evaluated for production feasibility using the full FBC model. Welding-induced distortion risk and a maximum mass increase criterion are applied as buildability filters to remove structurally admissible but practically high-risk solutions. The retained configurations are then re-evaluated using the complete FBC formulation to obtain consistent KPI comparisons.

Figure 3.7 provides an overview of the iterative interaction between the FBC model, the LR-based optimisation stage, and the final KPI-based evaluation.

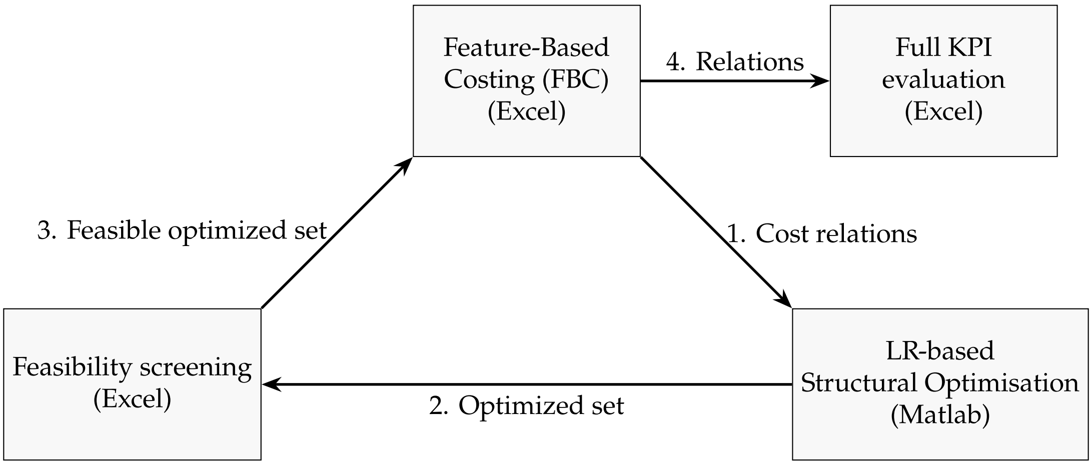


Figure 3.7: Iterative triangular workflow between FBC, optimisation, and cost-based selection.

3.3.2. Global feasibility space definition

To ensure that the quantitative analysis is performed within a realistic and practically relevant design domain, a unified global feasibility space is defined. This feasibility space specifies the adopted structural abstraction, the discrete parameter ranges, and practical shipyard constraints that bound the concept generation and KPI evaluation. Fabrication-related feasibility indicators that require detailed feature modelling (e.g. welding-induced distortion risk) are introduced in a subsequent screening stage.

For the purpose of the quantitative analysis, all structural arrangements are represented using a simplified equivalent stiffened panel abstraction. Complex three-dimensional structural layouts are reduced to idealised plate fields with regularly spaced longitudinal stiffeners and transverse webs. This abstraction enables a consistent and computationally tractable parameterisation of the design space. However, it is not intended to capture local geometric details, load redistribution effects, or secondary structural interactions. A schematic representation of the adopted stiffened panel abstraction is shown in Fig. 3.8.

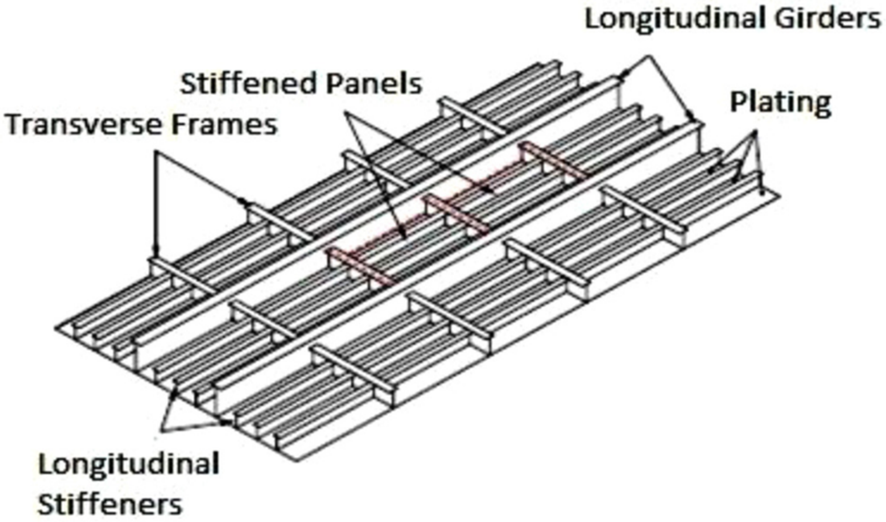


Figure 3.8: Equivalent stiffened panel abstraction used in the quantitative analysis [29]

Assumptions:

1. A girder is needed about every 3 stiffeners
2. Girder/web height is 2 x stiffener height
3. Web frames are placed every 1.5m
4. Brackets are used at every end of a stiffener
5. Buckling plates are placed at every 0.5m if needed
6. Tertiary elements have the same thickness as the thinnest member of the primary and secondary elements

The basis of the structure is based on the variables denoted below. Costs are governed by material specifications and the amount of labour needed, which for a simplified plate element are determined by structure weight and type, and part handling and weld length. All other scantlings like primary size and plate thicknesses are assumed to be related to these four variables, such as the assumptions below Fig. 3.8. Further relations and application will be elaborated in Section 3.3.3.

- plate thickness t_{plate},
- secondary stiffener profile size (HP profile),
- secondary stiffener spacing s_{stiff},
- web spacing a_{web}.

The feasibility space is constructed for a discrete set of reference panels extracted from a representative vessel. These reference panels define the geometric context and structural function of each panel type and serve as the baseline for expanding the feasibility space. A distinction is made between the reference stiffener spacing used for strength verification and that used for cost comparison. Fabrication costs are evaluated relative to existing *as-is* configuration, while structural strength calculations are referenced to a set of scantlings provided by De Voogt Naval Architects, which lay on the limit for Lloyd's Register compliance, or are governed by yard quality rules (shell above the waterline). The principal dimensions and characteristic structural parameters of the reference panels are summarised in Table 3.8.

Table 3.8: Reference panels used for the definition of the global feasibility space

Panel type	t_{plate} [m]	π_{HP}	$s_{\text{stiff,strength}}$ [m]	$s_{\text{stiff,cost}}$ [m]	s_{web} [m]	Notes
Weather deck	0.006	HP80×6	0.50	0.475	1.50	$s_{\text{stiff}} = 0.475$ m (reference panel); 0.50 m Lloyd's approved and adopted as feasible.
Inner decks	0.005	HP80×6	0.50	0.475	1.50	See weather deck notes.
Tanktop	0.006	HP80×6	0.50	0.475	1.50	See weather deck notes.
Bottom shell	0.008	HP80×6	0.50	0.35	1.50	See weather deck notes.
Shell (BW)	0.008	HP80×6	0.50	0.35	1.50	See weather deck notes.
Shell (AW)	0.007	HP80×6	0.35	0.35	1.50	See weather deck notes.

Based on these reference configurations, feasibility indicators related to bending stiffness and welding-induced distortion are evaluated. These indicators form the basis for the rule-based expansion of the feasible parameter sets described in the following subsection.

It is emphasised that the resulting feasible configurations should be interpreted as equivalent panel representations intended to reveal relative trends and sensitivities, rather than as detailed or directly buildable structural designs.

Practical yard constraints

Candidate configurations are restricted to practical shipyard constraints to ensure compatibility with existing production capabilities. The following constraints are applied:

- **HP profile availability (π_{HP}):** Only commercially available HP profiles are permitted.
- **Available plate thickness:** Plate thicknesses are restricted to standard commercially available values.
- **Size and handling constraints:** Upper bounds on component dimensions and weight are imposed to reflect yard handling, lifting and transportation limitations.

This feasibility space incorporates structural plausibility requirements and practical shipyard constraints. Additional fabrication-related performance indicators are introduced in subsequent sections.

It is emphasised that the resulting feasible configurations should be interpreted as equivalent panel representations intended to reveal relative trends and sensitivities, rather than as detailed or directly buildable structural designs.

Only configurations that satisfy the structural plausibility criteria, distortion limits, and practical yard constraints are retained for further evaluation. The subsequent subsection quantifies the production-related impact of these admissible configurations using a Feature-Based Costing (FBC) framework.

3.3.3. Quantification of KPI's

The mass, emissions, production time and costs of each structural panel is evaluated using a Feature-Based Costing (FBC) approach. Every structural component of a section is represented as a distinct *feature*, and all fabrication-related costs, including material, waste, cutting, forming, welding, and assembly, are attributed directly to these fetures based on historical yard data. Shipping cost is applied only at the level of the fully assembled structural unit, consistent with yard practice. A section is defined as the total area of a section type, being shell above waterline, shell beneath waterline, bottom shell, tanktop, inner deck, or weather deck.

Features

Each panel is decomposed into the following features:

1. **Plate**
2. **Primary members (webs, girders)**
3. **Secondary members** (secondary stiffeners)
4. **Brackets**
5. **Buckling strips**

Each feature f contains geometric and fabrication parameters that determine the KPI's.

Number of features

For a representative structural section with length L_{sec} and width W_{sec}, and for the number of structural components is determined using the following analytical expressions. These formulations are used to discretise the structure for cost estimation and other KPI's. Each type of panel has specified length and width dimensions, based on the CAD model of the ship used as case study. The panel types include: bottom shell, decks, strength deck, shell plating above the waterline and shell plating beneath the waterline. The rounding operator reflects the discrete nature of the number of members.

Number of plates

$$N_{\text{plate}} = \text{roundup}\left(\frac{L_{\text{sec}}}{L_{\text{plate}}} \frac{W_{\text{sec}}}{W_{\text{plate}}} \right) \tag{3.3.5}$$

where L_{plate} and W_{plate} denote the standard plate length and width, respectively. This expression represents the total number of plates required to cover all decks within the considered section.

Number of longitudinal girders

$$N_{\text{gir}} = \text{roundup}\left(\frac{W_{\text{sec}}}{s_{\text{gir}}} \right) \text{roundup}\left(\frac{L_{\text{sec}}}{L_{\text{prof}}} \right) \tag{3.3.6}$$

This formulation describes the number of longitudinal girders distributed over the section width, accounting for the standard delivered profile length.

Number of secondary stiffeners

$$N_{\text{stiff}} = \text{roundup}\left(\frac{W_{\text{sec}}}{s_{\text{stiff}}} - \frac{W_{\text{sec}}}{s_{\text{gir}}} \right) \text{roundup}\left(\frac{L_{\text{sec}}}{L_{\text{prof}}} \right) \tag{3.3.7}$$

Here, s_{stiff} is the spacing of secondary stiffeners, s_{gir} is the spacing of longitudinal girders, and L_{prof} is the standard profile length. The subtraction term removes secondary stiffeners coinciding with girder locations, preventing double counting.

Number of webs

$$N_{\text{web}} = \text{roundup}\left(\frac{L_{\text{sec}}}{a_{\text{web}}} \right) \text{roundup}\left(\frac{w_{\text{sec}}}{L_{\text{prof}}} \right) \tag{3.3.8}$$

where a_{web} denotes the web spacing.

Number of brackets

$$N_{\text{brackets}} = 2\,N_{\text{stiff}} \tag{3.3.9}$$

It is assumed that each stiffener ends at every second web frame and requires a bracket at each end.

Number of buckling plates

$$N_{\text{buckling}} = \begin{cases} 2\,\text{roundup}\left(\frac{L_{\text{sec}}}{a_{\text{web}}}\right)\,\text{roundup}\left(\frac{w_{\text{sec}}}{s_{\text{stiff}}}\right), & t_{\text{plate}} \leq 8\text{ mm} \\ 0, & t_{\text{plate}} > 8\text{ mm} \end{cases} \tag{3.3.10}$$

Buckling plates are only considered for thin plating ($t_{\text{plate}} \leq 8$ mm, $t_{\text{plate}} \leq 9$ mm for shell plating above the waterline). The number depends on the number of web bays along the section length and the number of stiffener bays across the section width. Between two consecutive longitudonal girders, two buckling strips are applied under the above thickness condition.

Mass determination of features

Once the number and dimensions of each structural feature are known, the total mass of each feature type can be determined. The mass is calculated by multiplying the total volume of the feature by the material density of steel.

For a given feature type i, the total mass is expressed as

$$m_i = \rho_{\text{steel}}\,V_i, \tag{3.3.11}$$

where ρ_{steel} is the density of steel and V_i is the total volume of feature type i.

The total mass of a given feature type is then calculated by

$$m_i = \rho_{\text{steel}}\,N_i\,V_{i,\text{single}}. \tag{3.3.12}$$

The total structural mass of the considered section is then obtained by summing the contributions of all feature types:

$$m_{\text{total}} = \sum_{i=1}^{n} m_i, \tag{3.3.13}$$

where n denotes the number of distinct structural feature types considered.

Weld length determination

The following assumptions are made for the weld length estimation. Each stiffener, girder, and web is welded on both sides along its length and at the two upstanding ends.

$$L_{\text{weld,stiff}} = \left(2\,l_p + 4\,h_{HP}\right)N_{\text{stiff}}, \tag{3.3.14}$$

$$L_{\text{weld,gir}} = \left(2\,l_p + 4\,h_p\right)N_{\text{girders}}, \tag{3.3.15}$$

$$L_{\text{weld,web}} = \left(2\,l_p + 4\,h_p\right)N_{\text{webs}}. \tag{3.3.16}$$

Each bracket has 2 weld sides of 200mm, and is welded double sided:

$$L_{\text{weld,bracket}} = 4 \cdot 200 \cdot N_{\text{brackets}}. \tag{3.3.17}$$

Each buckling plate covers 2/3 of the width of the stiffener spacing s_{stiff}:

$$L_{\text{weld,buckling}} = 2 \cdot 0.66\, s \cdot N_{\text{buckling}}. \tag{3.3.18}$$

The weld throat thickness on the thinnest connected welded member t_{min}:

$$a_{\text{weld}} = \begin{cases} 3 & t_{\text{min}} < 9 \\ 3.5 & 9 \leq t_{\text{min}} < 12 \\ 4 & 12 \geq t_{\text{min}} \end{cases} \tag{3.3.19}$$

Carbon dioxide emissions from material production and welding

The carbon dioxide (CO_2) emissions associated with the considered structural section are calculated directly from the previously determined masses of the structural features. All emissions are expressed in kilograms of CO_2, and only CO_2 emissions are considered (other greenhouse gases are neglected).

Two contributions are taken into account: 1. embodied CO_2 emissions from steel production and 2. process-related CO_2 emissions associated with MAG welding.

Steel production CO_2 emissions. Let m_{steel} denote the total steel mass of all structural features in the considered section [kg]. Using the steel production CO_2 emission intensity α_{steel} [kgCO$_2$/kg], the associated CO_2 emissions are given by

$$G_{\text{steel}} = \alpha_{\text{steel}}\, m_{\text{steel}}. \tag{3.3.20}$$

Welding CO_2 emissions (MAG). Let m_{weld} denote the total deposited weld metal mass [kg]. Using the MAG welding CO_2 emission intensity α_{weld} [kgCO$_2$/kg], the corresponding CO_2 emissions are

$$G_{\text{weld}} = \alpha_{\text{weld}}\, m_{\text{weld}}. \tag{3.3.21}$$

Total CO_2 emissions. The total CO_2 emissions of the considered structural section are obtained by summing the contributions from steel production and welding:

$$G_{\text{total}} = G_{\text{steel}} + G_{\text{weld}}. \tag{3.3.22}$$

Feature-level cost formulation

For each feature f, the total cost consists of material, waste, mass-based cutting and forming (for all non-plate features), transport, assembly, and welding costs.

Let m_f denote the mass of feature f, and let the total section mass be:

$$m_{\text{sec}} = \sum_f m_f. \tag{3.3.23}$$

Material and waste cost Material and waste are applied to all features:

$$C_{f,\text{mat}} = m_f \left(C_{\text{mat}}\right), \tag{3.3.24}$$

where C_{mat} is given in €/t.

Mass-based cutting and forming for non-plate features Cutting and forming costs are applied to all features except the plate, using mass-based historical cost rates.

Introduce an indicator function:

$$\chi_f = \begin{cases} 0, & \text{if } f \text{ is the plate or sec. stiffener,} \\ 1, & \text{otherwise.} \end{cases}$$

Then the cutting and forming cost becomes:

$$C_{f,\text{cut+form}} = \chi_f \, m_f \left(C_{\text{cut+form/t}} \right), \tag{3.3.25}$$

where $C_{\text{cut+form/t}}$ is in €/t.

Waste cost Waste costs are calculated for all structural members, excluding plates and secondary stiffeners. In accordance with yard practice, waste is assumed to correspond to 25% of an equivalent plate mass.

$$C_{f,\text{waste}} = \chi_f \, m_f \, C_{\text{waste/t}}, \tag{3.3.26}$$

where χ_f is the waste fraction, m_f is the mass of feature f, and $C_{\text{waste/t}}$ is the waste cost per unit mass, expressed in €/t.

Mass-based transport costs Transport costs are mass-based and derived from historical yard data and determined to be 25€/t. The total transportation costs are then calculated by:

$$C_{sec,\text{transp}} = \sum m_{\text{sec}} \, C_{\text{transp/t}},$$

(3.3.27)

Feature-level welding cost Welding cost is evaluated at feature level and is determined by the required welding time and the labour cost rate. The welding time depends on the total weld lenth, the effective welding speed, welder utilisation, and a section complexity factor accounting for reduced productivity in geometrically complex areas.

The effective welding time for feature f is given by

$$t_{f,\text{weld}} = \frac{L_{f,\text{weld}}}{v_{\text{weld}} \, \eta_{\text{weld}}}, \tag{3.3.28}$$

where $L_{f,\text{weld}}$ is the total weld length associated with feature f, v_{weld} is the nominal welding speed, η_{weld} is the welder utilisation factor. The utilisation factor is tuned to match historical welding data.

The corresponding welding cost is then calculated as

$$C_{f,\text{weld}} = t_{f,\text{weld}} \, C_{\text{lab}},$$

(3.3.29)

where C_{lab} denotes the welder labour cost rate.

Feature-Level Assembly Cost Assembly effort, including alignment, positioning, tack welding, and handling, is also feature-specific. Based on expert knowledge, each feature type is assigned an average assembly time $t_{f,\text{ass}}$:

$$C_{f,\text{assembly}} = t_{f,\text{ass}}\, C_{\text{lab}}.$$

(3.3.30)

Material cost determination of structural features

The material cost of each structural feature is determined by linking a feature-specific attribute (e.g. plate thickness or stiffener profile type) to a corresponding unit price obtained from internal company data. Unit prices are treated consistently in €/kg. The cost of each feature is then computed by multiplying the (previously determined) feature mass by the corresponding unit price.

Plates Let t_p denote the plate thickness used as lookup key. With plate mass m_{plate} [kg] and unit price $c_{\text{plate}}(t_{\text{plate}})$ [€/kg] from company data, the plate cost is

$$C_{\text{plate}} = m_{\text{plate}}\, c_{\text{plate}}(t_{\text{plate}}).$$

(3.3.31)

Secondary stiffeners Let π_s denote the stiffener profile type used as lookup key. With stiffener mass m_{stiff} kg and unit price $c_{\text{stiff}}(\pi_s)$ €/kg, the stiffener cost is

$$C_{\text{stiff}} = m_{\text{stiff}}\, c_{\text{stiff}}(\pi_s).$$

(3.3.32)

Primary members (longitudinal girders and transverse webs) Primary members are priced using a thickness-based primary pricing table from company data. The following assumption is applied:

$$t_{\text{gir}} = t_{\text{web}} = \begin{cases} 0.010\,\text{m}, & \text{for bottom structures,} \\ 0.008\,\text{m}, & \text{otherwise.} \end{cases}$$

With longitudinal primary mass m_{gir} and transverse primary (web) mass m_{web} kg, and unit price $c_{\text{plate,cut}}(t_{\text{gir}})$ €/kg, the costs are

$$C_{\text{gir}} = m_{\text{gir}}\, c_{\text{plate,cut}}(t_{\text{gir}}), \tag{3.3.33}$$

$$C_{\text{web}} = m_{\text{web}}\, c_{\text{plate,cut}}(t_{\text{web}}). \tag{3.3.34}$$

Tertiary members (brackets and buckling strips) Tertiary members are priced using a thickness-based tertiary pricing table from company data. The following assumption is applied:

$$t_{\text{tert}} = t_{\text{HP}}, \tag{3.3.35}$$

i.e. the tertiary member thickness equals the stiffener thickness.

Let t_s denote the stiffener thickness. With bracket mass m_{br} and buckling strip mass m_{buck} kg, and unit price $c_{\text{plate,cut}}(t_{\text{HP}})$ €/kg, the costs are

$$C_{\text{br}} = m_{\text{br}}\, c_{\text{plate,cut}}(t_{\text{HP}}), \tag{3.3.36}$$

$$C_{\text{buck}} = m_{\text{buck}}\, c_{\text{plate,cut}}(t_{\text{HP}}). \tag{3.3.37}$$

Total material cost The total material cost of the considered section is obtained by summing the contributions of all feature categories:

$$C_{\text{total,mat}} = C_{\text{plate}} + C_{\text{stiff}} + C_{\text{gir}} + C_{\text{web}} + C_{\text{br}} + C_{\text{buck}}. \tag{3.3.38}$$

Total cost calculation

The total cost of the section is then calculated by taking the sum of the previous calculated cost features, and is expressed by

$$C_{\text{total}} = C_{\text{total,mat}} + C_{\text{waste}} + C_{\text{tra}} + C_{\text{web}} + C_{\text{br}} + C_{\text{buck}}. \tag{3.3.39}$$

Lead time

To compare lead time between design alternatives, the total welding time $t_{\text{weld,tot}}$ and total assembly time $t_{\text{ass,tot}}$ are estimated. While this does not represent the complete production lead time (e.g. waiting, logistics, outfitting, and rework are not modelled), it provides a consistent proxy for differences in labour-driven production time between alternatives. The total lead-time proxy is defined as the sum of the welding and assembly time contributions.

$$t_{\text{weld,tot}} = \frac{C_{\text{weld,tot}}}{C_{\text{lab}}}, \tag{3.3.40}$$

$$t_{\text{ass,tot}} = \frac{C_{\text{ass,tot}}}{C_{\text{lab}}}, \tag{3.3.41}$$

$$t_{\text{lead,tot}} = t_{\text{weld,tot}} + t_{\text{ass,tot}}. \tag{3.3.42}$$

While the Feature-Based Costing (FBC) model establishes the production-related cost structure and quantifies the dominant fabrication drivers within the defined feasibility space, it does not generate new structurally admissible panel configurations. The FBC framework evaluates the production consequences of a given structural arrangement, but it does not determine the minimum scantlings required to satisfy classification-based strength criteria.

To systematically generate structurally feasible design variants, a rule-informed structural exploration step is required. This is performed through a Lloyd's Register (LR)–based panel optimisation procedure. The LR stage defines the minimum plate thickness and stiffener capacity required under the governing pressure envelope, thereby establishing the structurally admissible design space within which the previously derived production relations can be meaningfully compared.

3.3.4. Lloyd's-based panel generation

The preceding Feature-Based Costing (FBC) exploration established the production-driven cost structure of stiffened panels within the predefined feasibility space. It quantified how variations in plate thickness, stiffener spacing, and profile selection affect structural mass, weld length, part count, and fabrication cost. However, the FBC framework evaluates the production consequences of given configurations and does not determine whether those configurations satisfy classification-based structural requirements.

To ensure that only structurally admissible concepts are compared in subsequent analyses, a rule-informed structural generation step is introduced. The purpose of the Lloyd's Register (LR)–based panel generation stage is therefore to produce panel configurations that satisfy the LR pressure envelope in combination with calibrated analytical scantling relations.

This stage establishes the minimum plate thickness and stiffener capacity required for preliminary structural adequacy within the predefined feasibility space. It defines the structurally admissible design set upon which the previously derived production and cost relations can be consistently applied. The procedure remains limited to rule-informed screening and does not constitute full class verification or approval.

Buildability-related aspects such as welding-induced distortion risk, detailed fabrication practicality, and yard-specific qualitative preferences are not enforced within the LR-based stage itself. These aspects are evaluated separately in a subsequent production-feasibility screening using the Feature-Based Costing (FBC) framework.

Figure **??** provides a schematic overview of the adopted procedure. The LR-based stage functions primarily as a structured configuration generator and structural filter, producing rule-consistent candidate designs for further production-oriented evaluation.

For each combination of frame spacing a and stiffener spacing s, the minimum rule-compliant plate thickness and the smallest available stiffener profile satisfying the required section modulus are selected. The simplified strip-based cost formulation is subsequently evaluated to quantify relative cost trends within the generated configuration set.

The cost metric is not used to enforce global cost optimality at this stage, nor to promote intentionally heavier scantlings based on discrete price effects. Instead, it serves to characterise the cost implications of rule-driven structural choices and to enable a transparent comparison with the subsequent full Feature-Based Costing evaluation.

Configuration generation and selection procedure

For each panel type, structural configurations are generated through a systematic and fully discrete exploration of the design space. A visualisation of the full model is presented by Fig. **??**. The same procedure is applied to all panel types and ensures that only configurations satisfying the applied rule-based screening criteria are considered for further evaluation.

For a given panel type, all combinations of frame spacing a and longitudinal stiffener spacing s within the predefined feasibility space are evaluated. For each (a, s) combination, the governing Lloyd's Register design pressure is obtained from the LR shell pressure envelope. This pressure is used to determine a preliminary required plate thickness using the calibrated analytical thickness relation. The resulting thickness is then rounded up to the next commercially available plate thickness.

Based on the selected plate thickness, the effective attached plating width is calculated. This value is subsequently used to determine the required longitudinal stiffener section modulus according to the adopted analytical relations. A stiffener profile is selected from a discrete catalogue of HP sections as the profile with the smallest cross-sectional area that satisfies the calculated section modulus requirement.

Configurations for which no suitable stiffener profile is available, or which violate the optional elastic plate buckling screening criterion, are rejected and excluded from further consideration. For all remaining configurations that pass the applied screening steps, the simplified cost model described in Section 3.3.4 is applied to compute the equivalent strip cost per metre of ship length.

For each frame spacing a, the feasible configurations are ranked according to their equivalent strip cost. The lowest-cost configurations are retained for post-processing, visualisation and subsequent evaluation using the detailed Feature-Based Costing (FBC) model. This panel-level optimisation procedure is carried out independently for all relevant hull and deck zones. The resulting solution sets are then aggregated per panel type to enable comparative evaluation across the hull structure.

Baseline structural calculations

The starting point for the generation is a set of analytical scantling relations derived from classical stiffened-plate design theory. Each panel is idealised as an orthotropic plate stiffened in one direction, with the following geometric parameters:

- plate span between webs: a [m],
- stiffener spacing (panel bay width): s [m],
- design pressure acting normal to the plate: p [kN/m^2],
- material yield strength: σ_y [MPa],
- material safety factor: γ_M [-],
- allowable stress:

$$\sigma_{\text{allow}} = \frac{\sigma_y}{\gamma_M}.$$

The simplified expressions for the required plate thickness and stiffener section modulus follow well-established stiffened plate design relationships from classic ship structural design literature

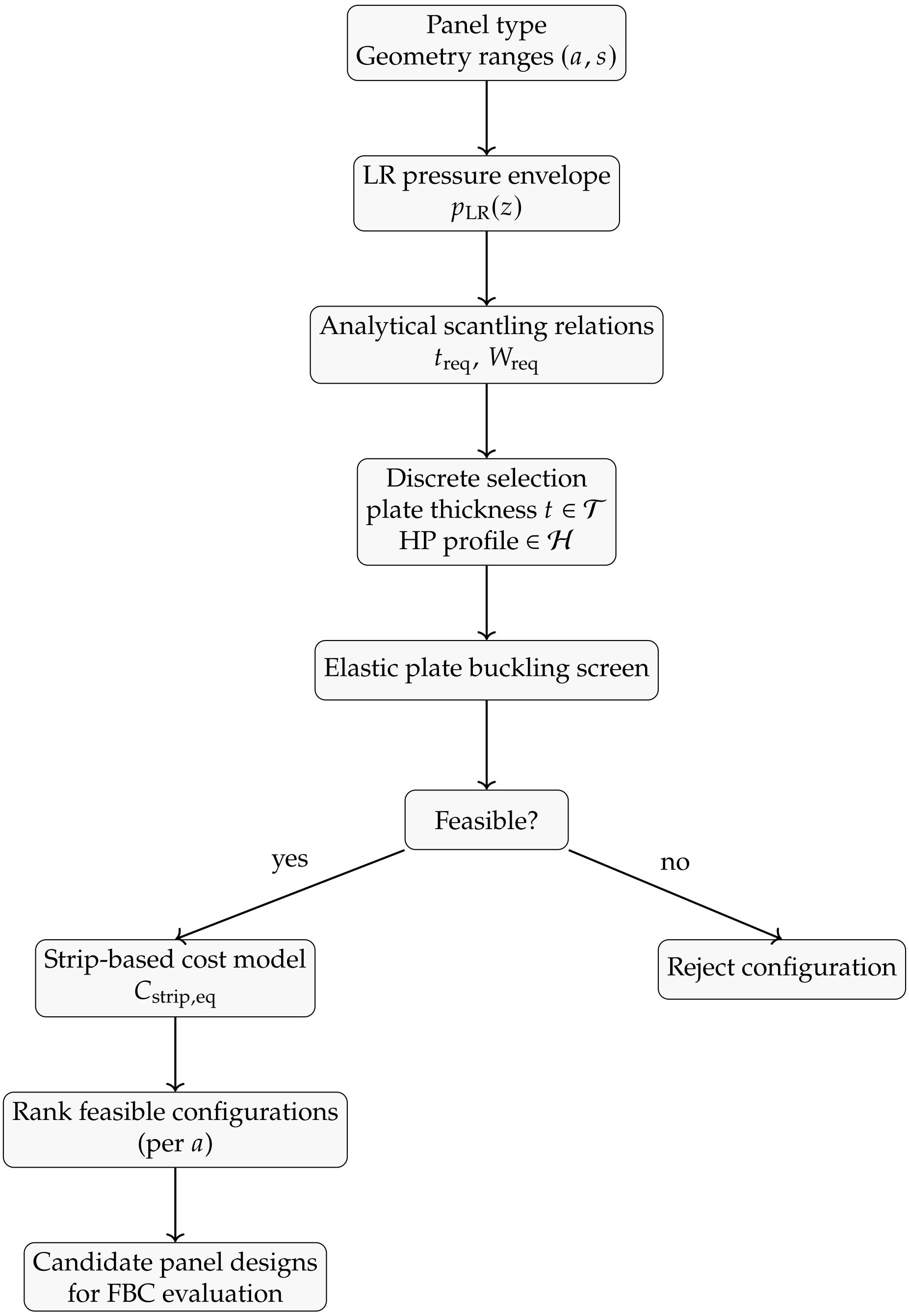


Figure 3.9: Workflow of the Lloyd's Register–based panel generation procedure.

parenciteTimoshenko1959,Hughes1988,Faulkner1975. These relations are derived from elastic plate bending theory and equivalent-beam modelling of stiffeners subjected to lateral pressure, combined with an allowable-stress criterion. They provide widely used scaling laws for first-yield design:

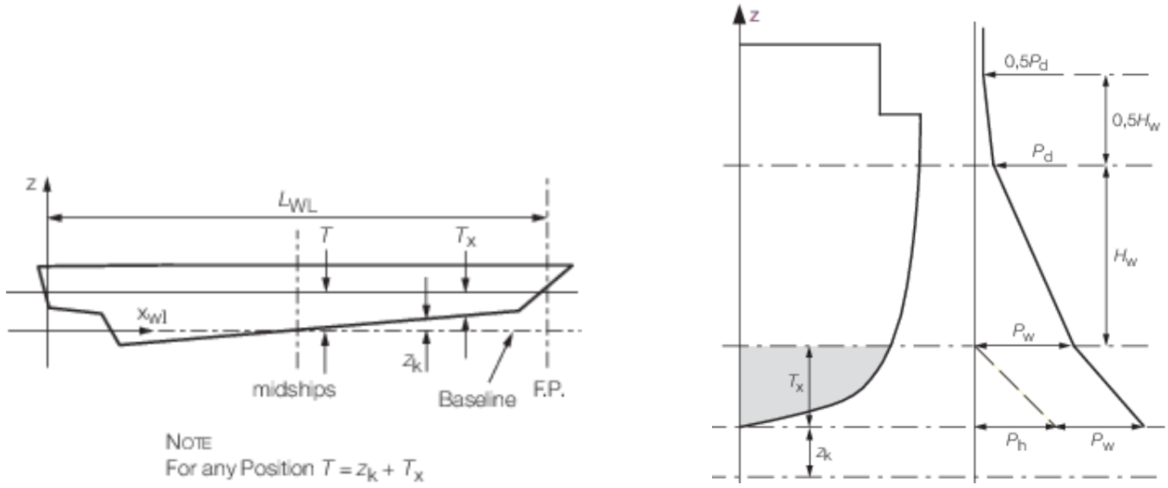
$$t_{\mathrm{req}} = k_t \sqrt{\frac{p\,s^2}{\sigma_{\mathrm{allow}}}}, \qquad W_{\mathrm{req}} = k_W \frac{p\,s\,a^2}{\sigma_{\mathrm{allow}}},$$

where:

- t_{req} is the required net plate thickness [mm],
- W_{req} is the required stiffener section modulus about the relevant bending axis [cm^3],
- p is the applied design pressure,
- k_t and k_W are calibration factors that account for boundary conditions, stiffener restraint, and the relative contributions of yielding, plate bending, and stiffener bending.

These analytical scantling relations are not tied to a specific rule set; instead, they represent first-principles structural behaviour and therefore form a compact and computationally efficient basis for parametric structural evaluation and design-space exploration. Their simplicity makes them well suited for rapid assessment of large discrete design spaces.

Lloyd's Register pressure envelope implementation



NOTE
For any Position $T = z_k + T_x$

(a) Definition of LR symbols used in the shell pressure formulation.

(b) Lloyd's Register shell pressure envelope as a function of vertical position.

Figure 3.10: Lloyd's Register shell pressure formulation and corresponding symbol definitions.

Table 3.9: Shell envelope pressure P_s as a function of vertical location z (adapted from LR Pt 5, Ch 2).

Vertical location (i.e. z value)	**Shell envelope pressure, P_s [kN/m^2]**
For $z \leq T_x + z_k$ (i.e. up to the operating waterline)	$P_h + P_w$
At $z = T_x + z_k + H_w$	P_d
At $z \geq T_x + z_k + 1.5H_w$	$0.5\,P_d$
Symbols	H_w is the nominal wave limit height. P_d is the weather deck pressure. P_h is the hydrostatic pressure. P_w is the hydrodynamic wave pressure. P_h and P_w are to be derived at the appropriate vertical position z. T_x is the draft at x from the aft z vertical distance, in metres, from the baseline to the position of centre of gravity of the item being considered. z_k vertical distance of the underside of the keel above the baseline, in metres.
Note	Pressure values at other z values are to be derived by interpolation.

Combined LR–classical stiffened plate design

Lloyd's Register (LR) provides several alternative procedures for determining minimum plate thicknesses and stiffener scantlings, including rule-based minimum values and location-dependent correction factors. While these procedures are well suited for the final verification of individual designs, their conditional structure and discrete formulation limit their applicability for systematic parametric optimisation and cost-driven design space exploration.

To enable consistent and transparent evaluation of a large number of design variants, the present study adopts a unified analytical modelling approach based on classical stiffened plate theory. In this framework, plate thickness and stiffener capacity are described using continuous closed-form relations, allowing for smooth variation of design parameters. The analytical relations capture the dominant structural behaviour of stiffened panels, namely local plate response between secondary stiffeners and the bending resistance of longitudinal stiffeners under external pressure loading.

Alignment with classification loading principles is achieved by deriving the governing design pressure directly from the Lloyd's Register shell pressure envelope. Rather than reproducing individual rule clauses or verification procedures, the applied pressure envelope is used to provide a rule-consistent loading basis for comparative and parametric evaluation within an early-stage design context.

The resulting analytical model is subsequently calibrated against representative Feadship Slob panel designs. This calibration aligns the analytical response with yard-proven structural proportions and typical scantling ranges while maintaining consistency with LR-based loading assumptions. The calibration step serves to anchor the model within realistic design boundaries and does not constitute class-compliant verification or approval.

By combining classical stiffened plate theory with Lloyd's Register design pressures, the proposed methodology provides a computationally efficient and transparent framework for parametric optimisation and production-oriented design evaluation. Structural feasibility is assessed within this combined modelling approach at a screening level, explicitly acknowledging that final class approval would require detailed rule-based verification and analysis beyond the scope of this study.

Within this combined methodology, the continuous design pressure p_{K} traditionally used in classical stiffened plate relations is replaced by the Lloyd's Register pressure envelope p_{LR}, as defined by the equations presented in Table 3.9. The governing analytical design relations therefore become:

$$t_{\text{req}} = k_t \sqrt{\frac{p_{\text{LR}}\, s^2}{\sigma_{\text{allow}}}}, \tag{3.3.43}$$

$$W_{\text{req}} = k_W \, \frac{p_{\text{LR}}\, s\, a^2}{\sigma_{\text{allow}}}, \tag{3.3.44}$$

where s is the stiffener spacing, a is the frame spacing, and σ_{allow} is the allowable normal stress.

Here, p_{LR} represents the governing Lloyd's Register design pressure acting on the panel, including hydrostatic, hydrodynamic, local, and internal load components. When this envelope-based pressure is inserted directly into the classical scantling relations, the resulting required plate thickness t_{req} and stiffener section modulus W_{req} are found to be significantly higher than the scantlings typically applied in comparable Feadship panels.

This discrepancy can be explained by two main effects:

- The coefficients used in classical stiffened plate relations implicitly reflect different ship types, loading assumptions, and safety margins than those applicable to one-off superyacht construction.
- In current yard practice, Feadship panels are designed and approved on a case-by-case basis, supported by detailed finite element analyses. This allows the use of lighter and more slender structures than would result from the direct application of generic analytical rule formulas.

As a result, a direct and unmodified application of classical stiffened plate relations combined with the LR pressure envelope would lead to overly conservative scantlings. To arrive at a realistic and practically usable design tool for the Slob panel family, the analytical relations are therefore recalibrated against existing yard practice.

Available stiffener capacity and Lloyd's effective width The analytical relations given in Eqs. (3.3.43)–(3.3.44) define the *required* plate thickness and stiffener section modulus. For each candidate panel configuration, the *available* stiffener capacity is evaluated separately. This capacity is determined as the combined contribution of the stiffener profile itself and the effectively attached plating, taking into account Lloyd's effective width concept.

The total available section modulus is expressed as

$$W_{\text{tot}} = W_{\text{HP}} + W_{\text{plate}}, \tag{3.3.45}$$

where W_{HP} is the section modulus of the stiffener profile and W_{plate} is the contribution of the adjacent plating acting compositely with the stiffener.

The plate contribution is determined using the Lloyd's Register effective width b_{eff}, such that

$$W_{\text{plate}} = \frac{b_{\text{eff}}\, t^2}{6}. \tag{3.3.46}$$

The effective width is calculated according to Lloyd's Register as

$$b_{\text{eff}} = \min\left(s,\ 2t\sqrt{\frac{E}{\sigma_{\text{allow}}}}\right), \tag{3.3.47}$$

and represents the portion of the adjacent plating that can be assumed to contribute effectively to stiffener bending resistance.

A stiffener configuration is considered structurally feasible if

$$W_{\text{tot}} \geq W_{\text{req}}. \tag{3.3.48}$$

Calibration of stiffened plate relations to reference panels

To align the analytical requirements t_{req} and W_{req} with the scantlings actually used at the shipyard, the coefficients k_t and k_W in Eqs. (3.3.43)–(3.3.44) are treated as calibration parameters.

Calibration targets and data set A representative set of existing Slob panels is selected for calibration. Each panel is characterised by:

- measured or specified plate thickness t_j^{ref},
- measured or specified stiffener section modulus W_j^{ref},
- geometric parameters (a_j, s_j),
- governing LR envelope pressure $p_{\text{LR},j}$,
- material properties $\sigma_{y,j}$ and partial safety factor $\gamma_{M,j}$.

For each panel j, the analytically predicted requirements are given by

$$t_j^{\text{mod}}(k_t) = k_t\sqrt{\frac{p_{\text{LR},j}\, s_j^2}{\sigma_{\text{allow},j}}}, \qquad \sigma_{\text{allow},j} = \frac{\sigma_{y,j}}{\gamma_{M,j}}, \tag{3.3.49}$$

$$W_j^{\text{mod}}(k_W) = k_W\, \frac{p_{\text{LR},j}\, s_j\, a_j^2}{\sigma_{\text{allow},j}}. \tag{3.3.50}$$

For the minimum required plate thicknesses, an additional Lloyd's-based rule constraint is applied:

$$\begin{aligned} t_{\text{min,bottom}} &= 8mm \\ t_{\text{min,shell BW}} &= 8mm \\ t_{\text{min,shell AW}} &= 7mm \end{aligned}$$

Tuning procedure for k_t and k_W The calibration aims to determine values of k_t and k_W such that the analytically predicted requirements correspond to the reference scantlings used in practice at Shipyard Slob. A least-squares fitting procedure is adopted.

The plate thickness calibration coefficient is obtained as

$$k_t = \arg\min(k) \sum_{j=1}^{N} \left(t_j^{\text{ref}} - k\sqrt{\frac{p_{\text{LR},j}\, s_j^2}{\sigma_{\text{allow},j}}} \right)^2, \tag{3.3.51}$$

while the stiffener section modulus coefficient is determined from

$$k_W = \arg\min(k) \sum_{j=1}^{N} \left(W_j^{\text{ref}} - k\, \frac{p_{\text{LR},j}\, s_j\, a_j^2}{\sigma_{\text{allow},j}} \right)^2. \tag{3.3.52}$$

The resulting calibrated coefficients k_t and k_W are subsequently applied in Eqs. (3.3.43)–(3.3.44) throughout the optimisation study. This yields an analytical model that is aligned with the Lloyd's Register loading philosophy and calibrated to reflect established Feadship Slob construction practice, while remaining explicitly limited to preliminary, rule-informed structural assessment.

Lightweight elastic plate buckling screen

In addition to the calibrated relations for plate thickness and stiffener sizing, a lightweight elastic plate buckling screen is included in the Lloyd's-envelope-based optimisation framework. The purpose of this screening step is to identify highly slender plate–stiffener configurations that are prone to elastic buckling of the plate field between longitudinal stiffeners.

The buckling check is intentionally formulated as a computationally inexpensive indicator. This allows a large number of (a, s) combinations to be evaluated efficiently, without the need for nonlinear finite element analyses.

Critical elastic buckling stress The plate field between two adjacent longitudinal stiffeners is idealised as a simply supported rectangular plate strip with width s, where s denotes the stiffener spacing. The classical expression for the elastic buckling stress under uniform compression is adopted as

$$\sigma_{\text{cr}} = k_{\text{buck}} \frac{\pi^2 E}{12\,(1-\nu^2)} \left(\frac{t}{s}\right)^2, \tag{3.3.53}$$

where E is Young's modulus, ν is Poisson's ratio, t is the selected plate thickness, and k_{buck} is the elastic buckling coefficient.

Rather than prescribing a single conservative constant, k_{buck} is here calibrated per panel type based on a reference Slob panel. For each panel type, a representative reference combination $(a_{\text{ref}}, s_{\text{ref}}, t_{\text{ref}})$ is defined, and k_{buck} is chosen such that

$$\sigma_{\text{allow}} = \sigma_{\text{cr,ref}} = k_{\text{buck}} \frac{\pi^2 E}{12\,(1-\nu^2)} \left(\frac{t_{\text{ref}}}{s_{\text{ref}}}\right)^2, \tag{3.3.54}$$

where $\sigma_{\text{cr,ref}}$ is the elastic buckling stress of the reference plate, σ_{allow} is the allowable normal stress used in the thickness calibration, and η_{buck} is a global safety margin. This implies

$$k_{\text{buck}} = \frac{\sigma_{\text{allow}}}{\dfrac{\pi^2 E}{12\,(1-\nu^2)} \left(\dfrac{t_{\text{ref}}}{s_{\text{ref}}}\right)^2}. \tag{3.3.55}$$

ensuring consistency between the reference plate design and the adopted buckling model.

Applied compressive stress proxy consistent with thickness calibration Within the optimisation framework, the required plate thickness is determined using a calibrated analytical relation of the form

$$t_{\text{req}} = k_t\, s \sqrt{\frac{p_{\text{LR}}}{\sigma_{\text{allow}}}}, \tag{3.3.56}$$

where p_{LR} is the governing Lloyd's Register envelope pressure for the considered panel location, σ_{allow} is the allowable normal stress, and k_t is a panel-type-dependent calibration coefficient obtained from reference Slob panels.

To evaluate buckling without introducing a separate detailed stress analysis, an applied compressive stress proxy is defined such that

$$\sigma_{\text{applied}} = \sigma_{\text{allow}} \quad \text{when} \quad t = t_{\text{req}}.$$

Substituting Eq. (3.3.56) yields

$$\sigma_{\text{applied}} = k_t^2\, p_{\text{LR}} \left(\frac{s}{t}\right)^2. \tag{3.3.57}$$

This formulation ensures full consistency between the plate thickness sizing relation and the applied stress proxy used for the buckling screen.

Buckling utilisation and interpretation A buckling utilisation factor is defined as

$$\text{util}_{\text{buck}} = \frac{\sigma_{\text{applied}}}{\eta_{\text{buck}} \sigma_{\text{cr}}}, \tag{3.3.58}$$

where σ_{cr} is the elastic critical buckling stress given by Eq. (3.3.53) and σ_{applied} is an equivalent in-plane stress derived from the lateral design pressure.

The factor η_{buck} is introduced as a global safety margin on elastic plate buckling and is set to

$$\eta_{\text{buck}} = 1.4. \tag{3.3.59}$$

Within the considered Slob design space, plate dimensions are governed by pressure requirements and minimum thickness criteria rather than by elastic buckling. Buckling is therefore treated as a non-governing limit state, and the relatively generous safety margin is adopted to provide robustness without influencing the cost-optimal designs.

Values $\text{util}_{\text{buck}} \leq 1$ correspond to plate fields for which the elastic buckling resistance, including the applied safety margin, exceeds the applied stress proxy.

In the present study, the buckling coefficient k_{buck} is calibrated per panel type such that the corresponding reference Slob panel yields, by calibration, a buckling utilisation of approximately $\text{util}_{\text{buck}} \approx 1$. Candidate configurations generated during the optimisation are rejected based on Eq. (3.3.58).

This modelling choice reflects practical shipbuilding reality. In service, ship structures are typically equipped with cosmetic buckling strips, which do not contribute to the structural capacity but influence the observed buckling behaviour, and benefit from fabrication-induced stiffening effects that are not explicitly captured in the optimisation model. The buckling check is therefore interpreted as a lightweight stability screen highlighting potentially critical slender designs, rather than as a hard design constraint.

Cost relations in LR-based optimisation

While the Lloyd's Register–based formulation described in the previous subsections ensures structural feasibility and rule compliance, it does not by itself provide a criterion for selecting one feasible panel configuration over another. To enable a cost-driven comparison between rule-compliant solutions, a simplified set of cost relations is embedded directly within the optimisation procedure.

The objective of this cost formulation is not to reproduce the full Feature-Based Costing (FBC) model introduced in Section 3.3.3, but to provide a computationally efficient surrogate cost function. This surrogate captures the dominant cost trends associated with variations in plate thickness, stiffener spacing, and stiffener profile selection. The LR-based optimisation thus serves as a rule-constrained cost screening step, after which selected configurations are re-evaluated using the detailed FBC model.

Cost modelling philosophy The cost model applied during the optimisation follows three guiding principles:

1. Only discrete, commercially available plate thicknesses and stiffener profiles are considered; interpolation between structural configurations is not permitted.
2. Absolute cost accuracy is not required at this stage; the objective is to identify relative cost trends and cost-efficient regions within the feasible design space.
3. Only dominant cost drivers that are directly influenced by the optimisation variables are included, in order to maintain computational efficiency.

Strip width selection and bay discretisation In the optimisation procedure, the effect of stiffener spacing is evaluated by varying the number of plate–stiffener bays over a finite transverse strip. Rather than modelling an infinitely wide panel, a fixed strip width is adopted, over which the number of bays changes discretely as a function of the stiffener spacing s.

A computational strip width of $B_{\text{strip}} = 100\,\text{m}$ is selected for this purpose. This width ensures that, within the investigated spacing range $0.3 \leq s \leq 0.8$ m, a sufficiently large number of discrete bay counts is obtained. As a result, cost trends associated with changes in stiffener spacing are captured smoothly, while preserving the discrete nature of physically realisable configurations.

Although stiffener spacings near the upper end of this range are not realistic in practice, a relatively large value of $s_{\max}$ is required to maintain sufficient sampling density in the practically relevant region. The optimisation therefore operates by implicitly varying the number of bays within the strip, rather than by continuously varying the strip width itself. The resulting modelling parameters become:

Table 3.10: Modelling parameters

Sample size	418 (209 at $a = 1.5\,\mathrm{m}$, 209 at $a = 1.8\,\mathrm{m}$)
Minimum step size s_{stiff}	0.001 m
Maximum step size s_{stiff}	0.007 m

For a given stiffener spacing s, the number of bays within the computational strip is defined as

$$n_{\mathrm{bay}} = \frac{B_{\mathrm{strip}}}{s}. \tag{3.3.60}$$

All cost components are first evaluated per bay and subsequently summed over n_{bay} bays to obtain the total cost per metre ship length for the 100 m wide strip.

Rescaling to a reference strip width To present results in a compact and practically interpretable form, the computed strip costs are linearly rescaled to a reference strip width of 3 m. The reported equivalent strip cost is therefore obtained as

$$C_{\mathrm{strip,3m}} = \frac{3}{100}\, C_{\mathrm{strip,100m}}. \tag{3.3.61}$$

This rescaling is valid because all cost components in the optimisation model scale linearly with the number of bays and, consequently, with strip width. The procedure preserves the relative contribution of material, welding, and fabrication-related costs, while enabling consistent comparison between configurations with different stiffener spacings.

Material cost relations Material costs are evaluated separately for plating and longitudinal stiffeners. The plate mass per bay is computed as

$$m_{\mathrm{plate}} = \rho_{\mathrm{steel}}\, s_{\mathrm{stiff}}\, t, \tag{3.3.62}$$

where t is the selected discrete plate thickness. The corresponding plate material cost is

$$C_{\mathrm{plate,mat}} = m_{\mathrm{plate}}\, c_{\mathrm{plate}}(t), \tag{3.3.63}$$

with $c_{\mathrm{plate}}(t)$ obtained from thickness-dependent yard price data.

The stiffener mass per bay is given by

$$m_{\mathrm{HP}} = \rho_{\mathrm{steel}}\, A_{\mathrm{HP}}, \tag{3.3.64}$$

leading to a stiffener material cost

$$C_{\mathrm{HP,mat}} = m_{\mathrm{HP}}\, c_{\mathrm{HP}}(\pi_{\mathrm{HP}}), \tag{3.3.65}$$

where A_{HP} and π_{HP} denote the cross-sectional area and profile type of the selected HP stiffener. The total material cost per bay is therefore

$$C_{\mathrm{mat,bay}} = C_{\mathrm{plate,mat}} + C_{\mathrm{HP,mat}}. \tag{3.3.66}$$

Welding cost proxy Welding cost is modelled using a simplified time-based formulation that captures the primary influence of plate thickness and weld length. Each bay is assumed to contain two longitudinal fillet welds connecting the stiffener to the plate, resulting in a fixed weld length per bay. The welding arc time is expressed as:

$$t_{\mathrm{arc}} = L_{\mathrm{weld}}\, k_{\mathrm{arc}}\, a_{\mathrm{weld}}, \tag{3.3.67}$$

where a_{weld} is the fillet weld throat size, selected discretely as a function of plate thickness following yard practice. The paid welding time accounts for welder efficiency, and the resulting welding cost per bay is

$$C_{\mathrm{weld,bay}} = \frac{t_{\mathrm{arc}}}{\eta_{\mathrm{weld}}}\, C_{\mathrm{lab}}. \tag{3.3.68}$$

Metal work and handling cost proxy Additional fabrication effort associated with handling, alignment, and fitting operations is represented by a metal work cost component, defined as a fixed ratio of the welding cost:

$$C_{\mathrm{metal,bay}} = \alpha_{\mathrm{mw}}\, C_{\mathrm{weld,bay}}, \tag{3.3.69}$$

where α_{mw} is derived from historical yard ratios between welding and associated metal work activities.

Transport costs Transport cost is treated as a purely mass-based component applied to the combined plate and stiffener mass per bay:

$$C_{\mathrm{trans,bay}} = (m_{\mathrm{plate}} + m_{\mathrm{HP}})\, c_{\mathrm{trans}}. \tag{3.3.70}$$

Total cost metric and its role in the LR-based optimisation The total cost per bay is obtained by summation of all contributing components:

$$C_{\mathrm{bay}} = C_{\mathrm{mat,bay}} + C_{\mathrm{weld,bay}} + C_{\mathrm{metal,bay}} + C_{\mathrm{trans,bay}}. \tag{3.3.71}$$

After scaling to strip level and applying equivalent-width normalisation, the resulting cost metric $C_{\mathrm{strip,eq}}$ is evaluated for every structurally admissible configuration.

Importantly, this LR-based stage is not intended as a true cost optimisation. Its primary purpose is to generate and filter *structurally feasible* scantling configurations based on the Lloyd's Register pressure envelope and calibrated analytical requirements. For each discrete (a, s) combination, the algorithm selects the *minimum* commercially available plate thickness and the *smallest* available HP profile that satisfy the rule-informed thickness and section-modulus requirements. This reflects the conventional assumption that, at fixed geometry, thinner plating and smaller stiffeners are typically associated with lower fabrication cost, due to lower material cost.

The cost metric $C_{\mathrm{strip,eq}}$ is therefore used as a *diagnostic comparison tool* rather than a strict selection objective. It allows a transparent comparison between (i) the simplified "minimum-scantling" selection implied by the LR-based sizing procedure and (ii) the more detailed KPI and cost evaluation obtained from the full Feature-Based Costing (FBC) model.

Because plate thicknesses are selected from a discrete set, the minimum required thickness is rounded up to the next commercially available value. In principle, non-linear yard price tables could imply that a thicker plate has a lower unit price (€/t) and might appear economically favourable. Such "over-thickening" purely to exploit material pricing effects is, however, considered unrealistic in one-off superyacht structural design and is therefore excluded by construction. Consequently, for each (a, s) combination the plate thickness is fixed as the minimum discrete thickness that satisfies the LR-informed requirement, and no deliberate increase beyond this minimum is allowed for cost reasons. Any cost differences reported for the LR-based stage therefore reflect only the cost implications of the rule-driven discrete selection, not an optimisation of plate thickness against material price irregularities.

3.3.5. Feasibility screening

The LR-based optimisation generates candidate configurations that are structurally admissible at screening level. The feasibility assessment in this section is therefore exclusively production-oriented: it evaluates whether these structurally admissible configurations remain practical and low-risk to fabricate at the shipyard.

Two buildability filters are applied:
(i) a welding-induced distortion risk criterion, and
(ii) a maximum allowable mass increase relative to the reference configuration.
Configurations that violate either criterion are removed from further KPI comparison.

Welding-induced distortion risk modelling

The adopted welding-induced distortion risk modelling approach is grounded in the inherent strain concept, which is widely accepted for evaluating welding deformation in large welded structures. Within this framework, the effect of welding is represented by an equivalent inelastic strain field that induces residual deformation in an otherwise elastic structural model. This approach was originally formalised by Okerblom [23] and later refined by Ueda et al. [35], who demonstrated that inherent strain methods provide an efficient means of assessing welding distortion without explicitly modelling the transient thermal process.

Rather than predicting absolute distortion magnitudes, inherent-strain-based approaches are commonly used to compare the relative distortion sensitivity of alternative structural configurations. This comparative application is particularly suited to early-stage design and Design-for-Production studies, where geometric trends and relative buildability are of greater interest than exact deformation values. Several authors emphasise that simplified distortion indicators are appropriate when welding procedures are held constant and geometric parameters dominate the response [19, 28].

For stiffened plate panels, welding distortion has been shown to scale with both the magnitude of welding-induced shrinkage and the geometric stiffness of the panel. Classical plate theory indicates that out-of-plane deformation increases with the square of the unsupported span and decreases with increasing bending stiffness [33]. In a welding context, this behaviour has been confirmed experimentally and numerically for shipbuilding structures, where increased stiffener spacing and reduced panel stiffness lead to significantly higher distortion levels [34, 25]. This provides the theoretical basis for using the ratio between panel bending stiffness and stiffener spacing squared as a geometric scaling parameter governing distortion sensitivity.

Based on this literature, the distortion response of a stiffened panel may be expressed in proportional form as

$$w \propto \frac{(\varepsilon^* \, t) \, s_{\text{stiff}}^2}{D}, \tag{3.3.72}$$

where ε^* represents an equivalent inherent strain induced by welding, t is the plate thickness, s_{stiff} is the stiffener spacing, and D denotes the equivalent bending stiffness of the stiffened panel. In this context, the bending stiffness D is not used as a structural acceptance criterion, but solely as a geometric scaling parameter governing distortion sensitivity.

Heat-input dependence The magnitude of the inherent strain is strongly influenced by welding heat input and weld length. Experimental investigations show that welding distortion increases with increasing heat input per unit length and with increasing weld line density [15, 34]. Consequently, the total heat input per unit area of plating is frequently used as a relative measure to compare distortion potential between different panel configurations, particularly when welding process parameters are kept constant.

The relationship between heat input and distortion is known to be non-linear when considered over a wide process range. Studies by Okerblom [23], Satoh and Terasaki [30], and more recently Liang et al. [17] demonstrate that angular distortion reaches a maximum as a function of the normalised heat input Q/t^2, after which further increases in heat input reduce curvature due to through-thickness heating effects. However, within the practical welding regimes used in shipyards, distortion increases approximately monotonically with heat input. For comparative design evaluation within this limited process window, heat input may therefore be used as a relative scaling parameter for inherent strain. Although the non-linear Q/t^2 behaviour is well established in welding distortion literature, it is not modelled explicitly in this study, as heat input is treated as a discretised process parameter rather than a continuous design variable.

All panel configurations are assumed to be fabricated using the same MAG welding process. Under this assumption, relative differences in distortion sensitivity are governed primarily by geometric characteristics of the panel rather than by variations in welding procedure [35, 23].

Thickness-dependent heat input To reflect typical yard practice, the weld rule-based thickness-dependent heat input is adopted:

$$Q(t) = \begin{cases} 0.489 \text{ kJ/mm}, & t \leq 6 \text{ mm}, \\ 0.697 \text{ kJ/mm}, & t > 6 \text{ mm}. \end{cases} \tag{3.3.73}$$

Within the plate thickness range considered, the applied heat input lies within a regime where increases in welding distortion scale approximately linearly with heat input. The heat input can therefore be used to compare the relative distortion sensitivity of alternative designs.

Welding distortion severity indicator

Welding distortion vulnerability is evaluated using a relative Distortion Risk Indicator (DRI), which synthesises established scaling relations from welding distortion literature into a single design-oriented metric [35, 19, 25]. The indicator is intended as a relative comparison measure and is not used to predict absolute deformation magnitudes.

The distortion severity for configuration i is defined as

$$S_i = \frac{E_{\mathrm{A},i}\,\phi_{a,i}}{K_i}, \tag{3.3.74}$$

where geometric distortion sensitivity is combined with effective welding heat input.

Geometric scaling of distortion sensitivity The geometric scaling parameter governing distortion sensitivity is defined as

$$K_i = \frac{D_i}{s^2_{\mathrm{stiff},i}}, \tag{3.3.75}$$

where D_i is the equivalent bending stiffness of the panel and $s_{\mathrm{stiff},i}$ is the secondary stiffener spacing. This formulation reflects classical plate theory and welding distortion studies, and is used exclusively as a relative geometric measure within the distortion risk assessment [33, 19].

Effective heat input For each configuration i, an effective line heat input per unit area is defined as

$$E_{\mathrm{A},i} = Q_i\,\Lambda_i, \tag{3.3.76}$$

where Q_i is the welding heat input [kJ/mm] and Λ_i is the weld line density, expressed as weld length per unit plate area [mm^{-1}] [15, 34].

Fillet size effect The influence of fillet weld size is incorporated through a linear scaling factor based on the weld throat size:

$$\phi_{a,i} = \frac{a_i}{a_{\mathrm{ref}}}, \tag{3.3.77}$$

where a_i is the fillet weld throat size of configuration i, and a_{ref} is the throat size of the reference configuration. This linear formulation is adopted as a transparent approximation in the absence of validated universal distortion models for fillet size effects [19, 34].

Geometric distortion sensitivity

Geometric sensitivity to distortion is captured by the relative slenderness:

$$\beta_i = \frac{s_{\mathrm{stiff},i}}{t_{\mathrm{plate},i}}$$

Relative distortion risk index

Distortion risk is evaluated relative to a reference panel that is known to be manufacturable without excessive distortion. Two relative indicators are defined:

$$\mathrm{DRI}_{S,i} = \frac{S_i}{S_{\mathrm{ref}}}, \qquad \mathrm{DRI}_{\beta,i} = \frac{\beta_i}{\beta_{\mathrm{ref}}},$$

where $\mathrm{DRI}_{S,i}$ expresses the relative distortion severity and $\mathrm{DRI}_{\beta,i}$ represents the relative slenderness of configuration i, both normalised with respect to the reference panel, denoted *ref*.

The use of relative indices enables direct comparison between alternative scantling configurations while anchoring the assessment to a baseline design with proven buildability. In this way, absolute prediction of distortion is avoided, and the focus is placed on comparative sensitivity with respect to known production experience.

Acceptance of a candidate configuration is defined by allowing a maximum increase of 5% in distortion risk relative to the reference panel:

$$\mathrm{DRI}_{S,i} \leq 1.05, \qquad \mathrm{DRI}_{\beta,i} \leq 1.05.$$

These threshold values are derived from linearised relations calibrated against existing panel designs and reflect a conservative engineering tolerance rather than a strict physical limit. The adopted margin represents a pragmatic balance between design flexibility and production robustness. While the exact upper boundary of acceptable distortion risk cannot be defined with certainty, the selected criterion provides a consistent and transparent acceptance envelope for comparative design evaluation within the scope of this study.

Distortion risk alone, however, does not fully capture the practical implications of adopting heavier and more widely spaced scantlings. Even when a configuration remains within the accepted distortion envelope, it may impose an undesirable increase in structural weight, affecting material consumption, handling effort, and downstream integration margins. A complementary mass-based constraint is therefore introduced to exclude solutions that achieve part-count reduction at the expense of excessive weight growth.

Mass increase constraint
To avoid impractical weight growth, a maximum allowable mass increase of 25% relative to the reference configuration is imposed:

$$\frac{m_i}{m_{\mathrm{ref}}} \leq 1.25.$$

Together, the distortion-risk criterion and mass constraint define the final production-feasibility acceptance set used for post-processing and KPI comparison. The following section outlines how the overall methodology is validated in terms of consistency, plausibility, and decision-support capability.

3.3.6. Methodological validation

The validation of the proposed framework focuses on its suitability as an early-stage decision-support tool for production-oriented structural design, rather than on the accuracy of absolute cost prediction. Given the bespoke and one-off nature of superyacht construction, validation is performed through a combination of calibration, internal consistency checks, plausibility assessment, and evaluation of decision-support capability.

3.3.7. Methodological validation

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Structural feasibility validation All design variants evaluated within the framework are subjected to the same structural feasibility constraints based on simplified plate theory and Lloyd's Register rule formulations. Configurations that violate stress, buckling, or deflection limits are systematically excluded. This will be validated and ensures that all quantitative comparisons are made exclusively between structurally admissible alternatives, preventing infeasible solutions from influencing the results.

Internal consistency and trend plausibility Internal consistency is assessed by systematically varying key structural design parameters and evaluating the resulting trends in production-related KPIs. The framework is considered internally consistent if changes in design parameters lead to monotonic, interpretable, and physically plausible responses in KPIs such as part count, weld length, production cost, and lead time. This validation step confirms that cause–effect relationships between design decisions and production outcomes are coherently represented.

Validation of cost structure ratios Although the absolute production effort is calibrated using historical hr/t values, the relative distribution between material, welding, and assembly cost components emerges from the underlying feature- and activity-based modelling. Validation is performed by assessing whether these relative cost contributions are explainable and consistent with historically observed production cost structures in steel hull construction. This step verifies that the internal cost structure behaves plausibly and is not an artefact of the calibration process.

Decision-support and trade-off capability The framework is validated as a decision-support tool by evaluating its ability to differentiate between structurally feasible design alternatives and to expose explicit trade-offs between competing performance indicators. Validation focuses on whether alternative designs produce distinct KPI profiles and whether improvements in production cost are accompanied by predictable trade-offs in secondary indicators such as structural mass, CO2 emissions, gross tonnage, or lead time. The framework is considered valid if no single design consistently dominates across all KPIs.

Robustness to modelling assumptions Finally, robustness is assessed by evaluating the sensitivity of relative results to reasonable variations in modelling assumptions and uncertainty parameters. The framework is considered robust if the qualitative ranking of design alternatives and the dominant trends remain stable under such variations, indicating that the conclusions are not driven by isolated parameter choices.

In summary, the proposed methodology is validated through feasibility filtering, internal consistency, plausibility of cost structure, and its ability to support informed trade-off analysis. Validation is explicitly framed in terms of comparative behaviour and decision-support capability, rather than absolute cost accuracy.

Concluding remarks on the methodology

The developed methodology integrates production-oriented cost modelling with rule-informed structural panel generation and buildability screening. First, the Feature-Based Costing (FBC) framework established quantitative relations between scantling parameters and key production drivers such as mass, weld length, part count, emissions, and fabrication cost. Subsequently, the Lloyd's Register–based panel generation stage defined the structurally admissible design space using calibrated analytical relations under a rule-consistent pressure envelope. Finally, distortion risk indicators and mass increase constraints ensured that retained configurations remain practically manufacturable within established yard tolerances.

The result of this integrated workflow is a structured set of panel configurations that are structurally plausible, production-feasible, and quantitatively comparable across multiple performance indicators. Rather than yielding a single optimal design, the framework produces transparent KPI relations that expose trade-offs between structural adequacy, fabrication complexity, and cost behaviour.

The following chapter presents the results of this parametric exploration. The generated configuration sets are analysed per panel type, and the resulting KPI trends are interpreted with respect to production efficiency, distortion sensitivity, and cost performance.

4

Results

This chapter presents the results of the qualitative guideline prioritisation and the subsequent quantitative scantling evaluation introduced in Chapter 3. The structure of this chapter mirrors the methodological phases: (i) the IAR-based guideline ranking, and (ii) the quantitative Feature-Based Costing (FBC) exploration combined with LR-based optimisation and post-processing. Since the quantitative phase aims to evaluate structural complexity reduction within admissible engineering boundaries, the results are first presented in terms of the global feasibility space. Only after structural admissibility is established can production-oriented KPIs and cost implications be meaningfully interpreted.

4.1. Quantitative Criteria Analysis

This section quantifies the impact of the selected design-oriented guidelines using the unified feasibility space, the feature-based KPI model, and the LR-based optimisation procedure described in Chapter 3.

Table 4.1: Reference panel dimensions used in feasibility assessment

	Bottom shell	**Shell below WL**	**Shell above WL**	**Weather deck**	**Tanktop**	**Inner decks**
N_{panel} [-]	1	2	2	1	1	2
L_{panel} [m]	60	30	60	40	60	40
B_{panel} [m]	10	5	3	10	10	10

4.1.1. Global feasibility space implementation (FBC-model)

This subsection establishes the basis for the global feasibility space used in the optimisation. As discussed in Section 3.3.2, the manufacturability of each stiffened panel configuration is assessed relative to a reference panel. To enable direct comparison, two normalised indicators are introduced: the slenderness-based index, DRI_β, and the heat–input–based distortion index, DRI_S. Both represent relative amplification factors of distortion sensitivity, where values exceeding unity indicate an increased deformation risk compared to the reference configuration.

Table 4.2 summarises the reference benchmark values for plate slenderness β_{ref} and distortion severity S_{ref} across the selected panel types. Because these values are derived from as-built Feadship configurations, they implicitly represent solutions that are known to be constructible without excessive welding distortion.

To avoid penalising local differences between functionally distinct panel locations, corrected limits are introduced for both indicators. The terms $\beta_{\text{max,corr}}$ and $S_{\text{ax,corr}}$ represent admissible upper bounds on slenderness and heat–induced deformation severity, respectively. These corrected values reflect the highest deformation sensitivities empirically tolerated in real-world production without violating alignment and fairness requirements. Only the shell above the waterline retains its uncorrected reference limits, due to more stringent fairness and cosmetic tolerances imposed on visible topside surfaces.

Acceptance in the feasibility check therefore requires

$$\mathrm{DRI}_{\beta,i} \leq 1.05, \qquad \mathrm{DRI}_{S,i} \leq 1.05.$$

Table 4.2: Feasibility check results for reference panel configurations

	Bottom shell	**Shell below WL**	**Shell above WL**	**Weather deck**	**Tanktop**	**Inner decks**
β_{ref} [m/m]	62.50	62.50	50.00	83.33	83.33	**100.00**
$\beta_{\mathrm{max,corr}}$ [m/m]	100.00	100.00	–	100.00	100.00	–
S_{ref} [J/(N m)]	35.39	35.39	30.46	58.86	58.86	**101.71**
$S_{\mathrm{ax,corr}}$ [J/(N m)]	101.71	101.71	–	101.71	101.71	–

While the global feasibility space defines structurally admissible design configurations, it does not yet provide insight into their production-related implications. To translate structural admissibility into quantifiable performance indicators, the Feature-Based Costing model is first applied to representative reference panels. This establishes internally consistent KPI relations that serve as the basis for subsequent optimisation and comparison.

4.1.2. Reference-panel KPI formulation and benchmarking (FBC)

To establish the KPI relations used in the optimisation procedure and to provide a reference for interpreting the output of the FBC cost model, a benchmarking exercise is performed based on representative stiffened-panel configurations. Due to confidentiality, the reference benchmarks are presented in the Annex. **??**. These configurations correspond to the reference panels defined in Table 3.8 and reflect typical geometric arrangements used in Feadship hull construction.

It should be noted that the KPI values reported here do not represent the full manufacturing detail of an as-built vessel. Instead, they are derived from simplified stiffened-plate abstractions that preserve characteristic dimensions, frame spacing and stiffening logic from current Feadship practice. The objective of this benchmark is therefore not to replicate absolute part counts or production quantities, but to generate internally consistent scaling relations for part count, weld length, mass, emissions, lead time and cost.

This subsection evaluates the reference panels in terms of their part-count composition, after which the corresponding production-related KPI trends are introduced.

Cost structure breakdown

Table 4.3 presents the relative distribution of material, metal work, and welding costs for all *as-is* analysed panel configurations. To assess the plausibility of the calibrated FBC model prior to optimisation analysis, the relative distribution of production cost components is examined for the analysed reference panel configurations.

Table 4.3: Relative distribution of production cost components for analysed as-is panel configurations

Panel configuration	**Material**	**Metal work**	**Welding**	**Welding / Metal work**
Deck	19%	49%	32%	0.65
Weather deck	21%	47%	31%	0.66
Above WL	18%	51%	31%	0.62
Below WL	22%	46%	32%	0.69
Tank top	21%	48%	32%	0.66
Bottom	23%	45%	32%	0.71

Although absolute production cost figures are confidential, historical yard data indicate that labour-related activities typically account for approximately 85% of total steel hull production cost, with the remaining 15% attributed to material and ancillary cost components. Within the labour component, the distribution between metal work and welding effort is generally observed to approximate a 60/40 ratio.

The modelled cost distributions presented in Table 4.3 show labour shares between 78% and 82%. Considering that the present analysis is based on simplified stiffened-panel abstractions and excludes a portion of outfitting-related activities, this deviation remains consistent with expected industrial variation. The welding-to-metal-work ratios also align closely with the historically observed 60/40 relationship.

These findings support the plausibility of the calibrated FBC structure and indicate that the internal cost composition emerges from the underlying feature-based modelling rather than being imposed through calibration assumptions.

Table 4.3 further demonstrates that, across most analysed panel configurations, the relative distribution between metal work and welding remains stable despite variations in scantling strategy and part count. Material cost shares exhibit moderate variation between configurations, reflecting differences in plate thickness, stiffener density, and structural integration.

4.1.3. LR-based panel optimisation results

This subsection presents the results of the Lloyd's Register (LR)-based panel optimisation and discusses their implications for both structural design and cost performance. The governing LR pressure envelope is first introduced to define the loading conditions applied to the different panel types, after which the calibration outcomes of the analytical stiffened-plate relations are presented. These calibrated coefficients are derived to align the optimisation model with yard-approved reference panels and ensure that the analytical formulation reflects current production practice.

The calibrated model is subsequently applied within a MATLAB-based optimisation framework to evaluate the influence of stiffener spacing and scantling choices on total construction cost. To assess the validity and practical relevance of the optimisation output, selected configurations are exported to the more detailed Feature-Based Costing (FBC) model, enabling a direct comparison between the analytical optimisation results and a higher-fidelity cost evaluation. This comparison is used to verify consistency in overall cost trends and to identify systematic deviations arising from differences in modelling assumptions and level of detail.

Based on the combined optimisation and cost evaluation results, a feasible and practically relevant stiffener spacing range is defined for subsequent analyses. This refined design space balances material efficiency, production effort, and structural mass constraints, and provides a consistent basis for the remainder of the optimisation study.

LR shell envelope result

Calibration outcomes per panel type

Table 4.4 summarises the calibrated coefficients k_t and k_W obtained for each panel type. These coefficients scale the classical stiffened plate relations such that the analytically predicted plate thicknesses and stiffener section moduli correspond to reference Slob panels under the governing Lloyd's Register pressure envelope.

The coefficients are treated as fixed model parameters throughout the remainder of the optimisation study. They are not optimisation variables and should therefore be interpreted as calibration outcomes rather than design results.

Interpretation of calibration outcomes The calibrated coefficients in Table 4.4 reveal clear and physically consistent differences between panel types. For bottom shell and shell panels below the waterline, identical values of k_t and k_W are obtained, reflecting the use of the same reference geometry and stiffener profile for these panels. Differences between these panel types are therefore introduced exclusively through the governing Lloyd's Register pressure envelope rather than through the structural scaling coefficients.

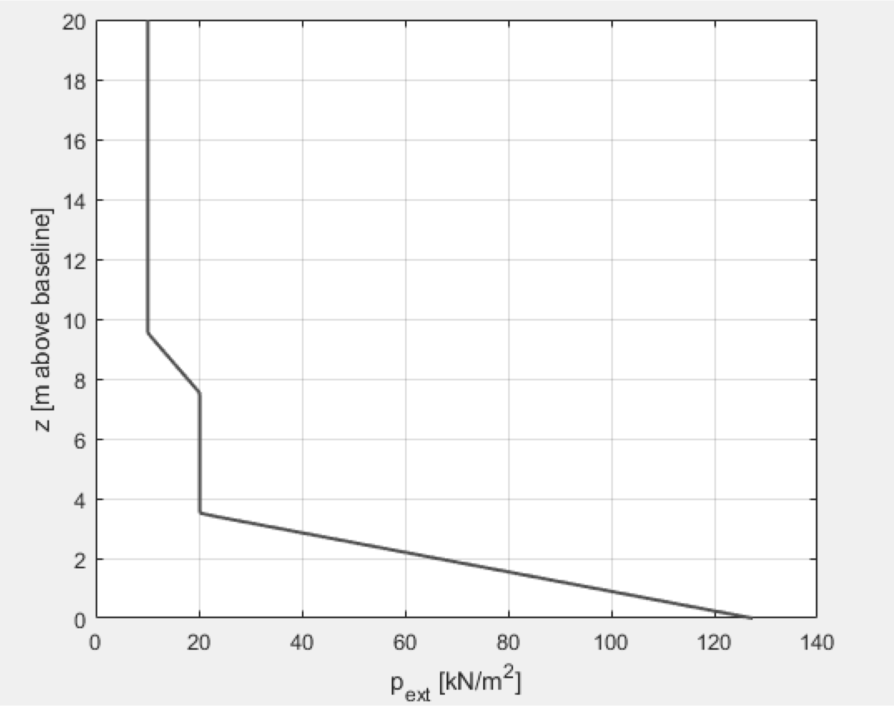


Figure 4.1: Lloyds-based shell envelope

Table 4.4: Calibrated stiffness coefficients for LR-based stiffened plate relations per panel type.

Panel type	$p_{\text{ext}}[Pa]$	k_t	k_W
Bottom shell	$1.25 \cdot 10^5$	0.6867	0.1729
Shell below waterline	$8.20 \cdot 10^4$	0.8567	0.2691
Shell above waterline	$2.12 \cdot 10^4$	2.1069	1.2195
Weather deck	$2.12 \cdot 10^4$	1.2641	0.8087
Tanktop	$1.01 \cdot 10^4$	1.8345	1.7032
Inner decks	$5.00 \cdot 10^3$	2.1679	3.1222

For shell panels above the waterline and the weather deck, substantially higher values of k_t are observed. This is caused by the buildability restrictions of these panels. In order to keep the sheel plates within deformation margins, the maximum stiffener spacing is limited to 50 times the plate thickness. This results in a high K_t in order to match reference Slob practice, for which yard-approved plate thicknesses are governed less by strength demand and more by practical minimum thickness considerations.

The stiffener coefficient k_W remains identical for bottom shell, shell below the waterline, and weather deck panels, as these panel types are calibrated against the same stiffener geometry. In contrast, a significantly lower value of k_W is obtained for shell panels above the waterline, which use a lighter reference stiffener profile. This confirms that k_W primarily captures the structural efficiency of the chosen stiffener–plate combination rather than differences in loading magnitude.

Overall, the calibrated coefficients demonstrate that the unified analytical formulation can be consistently aligned with yard practice across multiple panel types, while preserving the distinction between loading effects, captured by the LR pressure envelope, and structural scaling effects, captured by k_t and k_W.

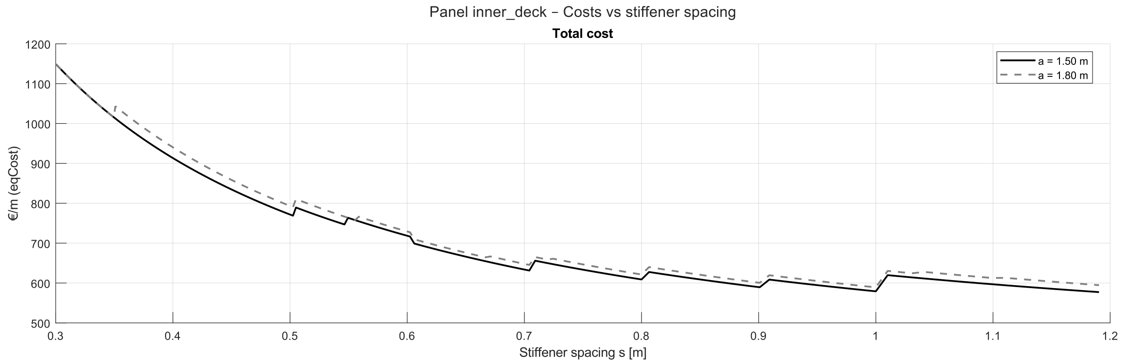
Initial evaluation Matlab through FBC-model

To evaluate the total cost output of the MATLAB-based optimisation, which considers only plate elements and secondary stiffeners, the resulting inner deck configurations are exported to the more detailed Feature-Based Costing (FBC) model. The FBC framework requires only a limited set of geometric inputs from the optimisation, namely the plate thickness t_{plate}, stiffener profile type π_{HP}, stiffener height

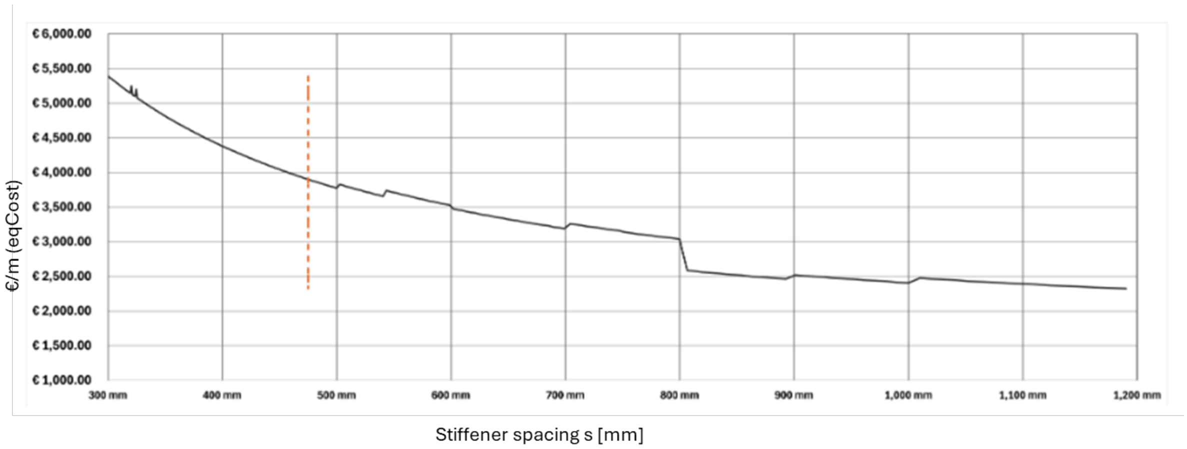
h_{HP}, stiffener thickness t_{HP}, stiffener spacing s_{stiff}, and transverse frame spacing a_{web}. All remaining geometric details and process parameters within the FBC model are deterministically derived from these inputs, following the yard-specific design and production rules described in Section 3.3.3.

To ensure a consistent comparison between the analytical optimisation and the detailed cost evaluation, the total section costs obtained from the FBC model are normalised to the same representative panel dimensions as used in the MATLAB optimisation, namely a strip width of $B_{\mathrm{strip}} = 3\,\mathrm{m}$ and a longitudinal length of $a_{\mathrm{strip}} = 1\,\mathrm{m}$.

The results of the MATLAB optimisation and the corresponding FBC cost evaluation are shown in Figs. 4.2a and 4.2b, respectively.



(a) MATLAB optimisation result: total equivalent strip cost as a function of stiffener spacing for inner decks.



(b) Feature-Based Costing (FBC) evaluation of selected MATLAB-optimal inner deck configurations (cost component breakdown).

Figure 4.2: Comparison of optimisation output vs FBC output

When comparing the optimisation output with the Feature-Based Costing (FBC) evaluation, it is immediately evident that both approaches exhibit a very similar overall cost trend as a function of stiffener spacing. This indicates that, despite the difference in modelling fidelity, both methods capture the underlying relationship between stiffener spacing and total construction cost in a consistent manner. The higher absolute cost level predicted by the FBC model is expected, as it explicitly accounts for primary, secondary, and tertiary structural members, as well as additional assembly and welding operations. As a result, more material is included and more production effort is required. Up to this point, the observed behaviour is fully consistent with engineering expectations.

A closer inspection of the cost curves reveals that the trends are nearly identical, with one notable exception. At a stiffener spacing of $s_{\mathrm{stiff}} = 0.8$ m, the MATLAB-based optimisation shows a distinct increase in total cost. This discontinuity is caused by a step increase in the selected plate thickness, which results from the use of discrete, commercially available plate thicknesses in the optimisation. The corresponding increase in plate thickness leads to a significant rise in material cost.

At identical stiffener spacing, the FBC model predicts a reduction in total cost, in contrast to the MATLAB-based model. This discrepancy can be explained by the modelling assumptions related to buckling plates. As discussed in Section 3.3.3, buckling plates are required only for plate thicknesses up to 7 mm for decks and 8 mm for shell plating. Once the required plate thickness increases to 8 mm, the use of buckling plates is eliminated. The removal of buckling plates leads to a substantial reduction in labour and welding costs, while the associated increase in material cost due to the thicker plate remains relatively limited. As a result, the total cost decreases in the FBC evaluation at this stiffener spacing, whereas the MATLAB model captures only the material-driven cost increase and therefore predicts a higher total cost.

Further analysis shows that, although the elimination of buckling plates significantly reduces the number of structural components, no reduction in total structural mass is observed at this point. Instead, the rate of mass increase is reduced. This indicates that the increase in structural mass resulting from the thicker plating outweighs the mass reduction achieved by removing the buckling plates, as illustrated at $s_{\text{stiff}} = 0.8$ m.

With the cost trends established, an optimal range for stiffener spacing can be defined. First, it is observed that reducing the stiffener spacing below the reference configuration does not lead to lower total costs in any case. This behaviour is highlighted by the orange reference line and implies that the minimum stiffener spacing can be fixed at the reference value for subsequent analyses.

Second, an upper bound on stiffener spacing must be imposed. This bound is defined based on an allowable increase in structural weight, limited to a maximum of 125% of the reference construction mass, as evaluated using the FBC model. The resulting total construction mass is shown in Figure 4.3, where the orange line indicates the 125% mass limit. For inner decks, this criterion corresponds to a maximum stiffener spacing of approximately 0.6 m.

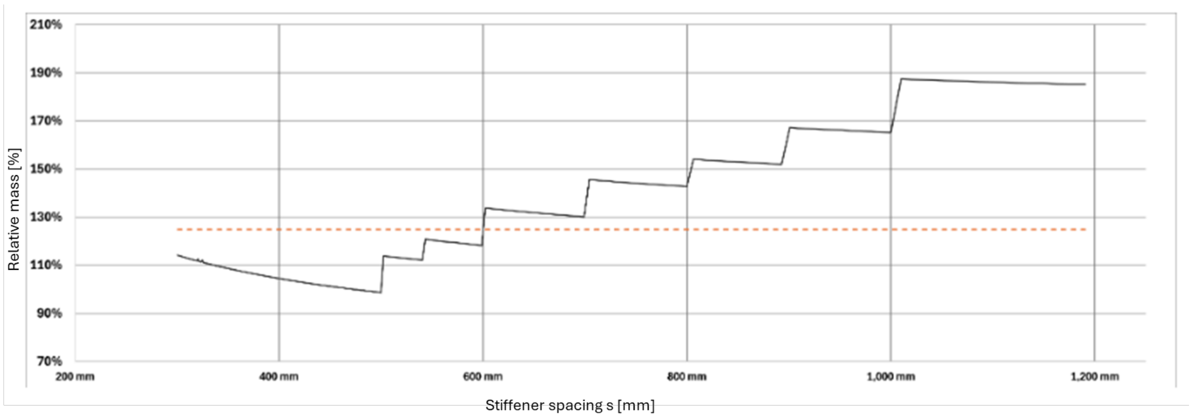


Figure 4.3: Optimisation output relative constructional mass

As the mass–spacing relationship is expected to vary between different panel types, a conservative global spacing range of

$$0.3\text{ m} < s_{\text{stiff}} < 0.8\text{ m} \tag{4.1.1}$$

is adopted for the MATLAB optimisation. In addition, the modelling strip length L_{strip} is reduced from 100 m to 18 m to limit the total number of evaluated configurations. This reduces the sample size from approximately 418 to 76 configurations per panel type, significantly improving computational efficiency. Within this range, the number of stiffeners varies between 22 and 60, resulting in spacing increments between approximately 5 mm and 36 mm. Larger spacing steps occur only near the upper bound of the spacing range, where such configurations are already considered impractical for real ship structures. The results of the new design space are evaluated in the next section.

Optimisation results for costs vs stiffener spacing

To identify the influence of stiffener spacing on the different cost drivers, the stiffener spacing s is varied between 0.30 m and 0.8 m, as introduced in Section 3.3.4. In this section, the resulting material, welding, metal-work and transport costs are evaluated for all panel types.

Across all panel types, the individual cost components exhibit a number of consistent trends as a function of stiffener spacing. Material costs generally increase in a stepwise manner, driven by the discrete selection of plate thicknesses imposed by the market available plate thicknesses. In addition, non-monotonic behaviour may occur due to the discrete plate pricing used in the cost model, in which the price per tonne is not strictly increasing with plate thickness. For smaller frame spacing, small stiffeners will comply with the required section modulus, and are therefore dominated by plate thickness discretisation. For larger frame spacings, changes in the selected stiffener profile can also be observed, and are presented by small discrepancies in material cost.

Transport costs vary stepwise with stiffener spacing, as they scale linearly with steel mass and are, like the material costs, affected by discrete plate thicknesses and stiffener profile availability. The total cost curves reflect the total sum of these contributions and therefore, reflect a decreasing trend, with stepwise increases, due to the increases in material costs and weld throat thickness.

Bottom shell results Figure 4.4 shows the cost breakdown for bottom shell panels as a function of the stiffener spacing s, evaluated for frame spacings $a = 1.50\,\mathrm{m}$ and $a = 1.80\,\mathrm{m}$.

The bottom shell results follow a largely regular and predictable trend over the investigated stiffener spacing range. A clear distinction is observed between the results for $a = 1.50\,\mathrm{m}$ and $a = 1.80\,\mathrm{m}$. For $a = 1.50\,\mathrm{m}$, the cost curves do not exhibit smaller intermediate steps associated with stiffener profile changes, indicating that a single stiffener profile remains sufficient over the full spacing range. In contrast, for $a = 1.80\,\mathrm{m}$ such smaller step changes occur regularly, corresponding to transitions to larger stiffener profiles.

This difference is explained by the larger frame spacing, which increases the tributary area per stiffener and therefore the total line load acting on the stiffener. As a result, the required section modulus increases more rapidly with stiffener spacing for $a = 1.80\,\mathrm{m}$, triggering earlier and more frequent stiffener profile upgrades.

The cost-optimal solution are found at $s_{\mathrm{stiff}} = 0.625\,\mathrm{m}$ and $s_{\mathrm{stiff}} = 0.746\,\mathrm{m}$. It is noteworthy that $s_{\mathrm{stiff}} = 0.50\,\mathrm{m}$ corresponds exactly to the reference panel configuration, indicating that the reference design is already close to a local cost optimum for this panel type.

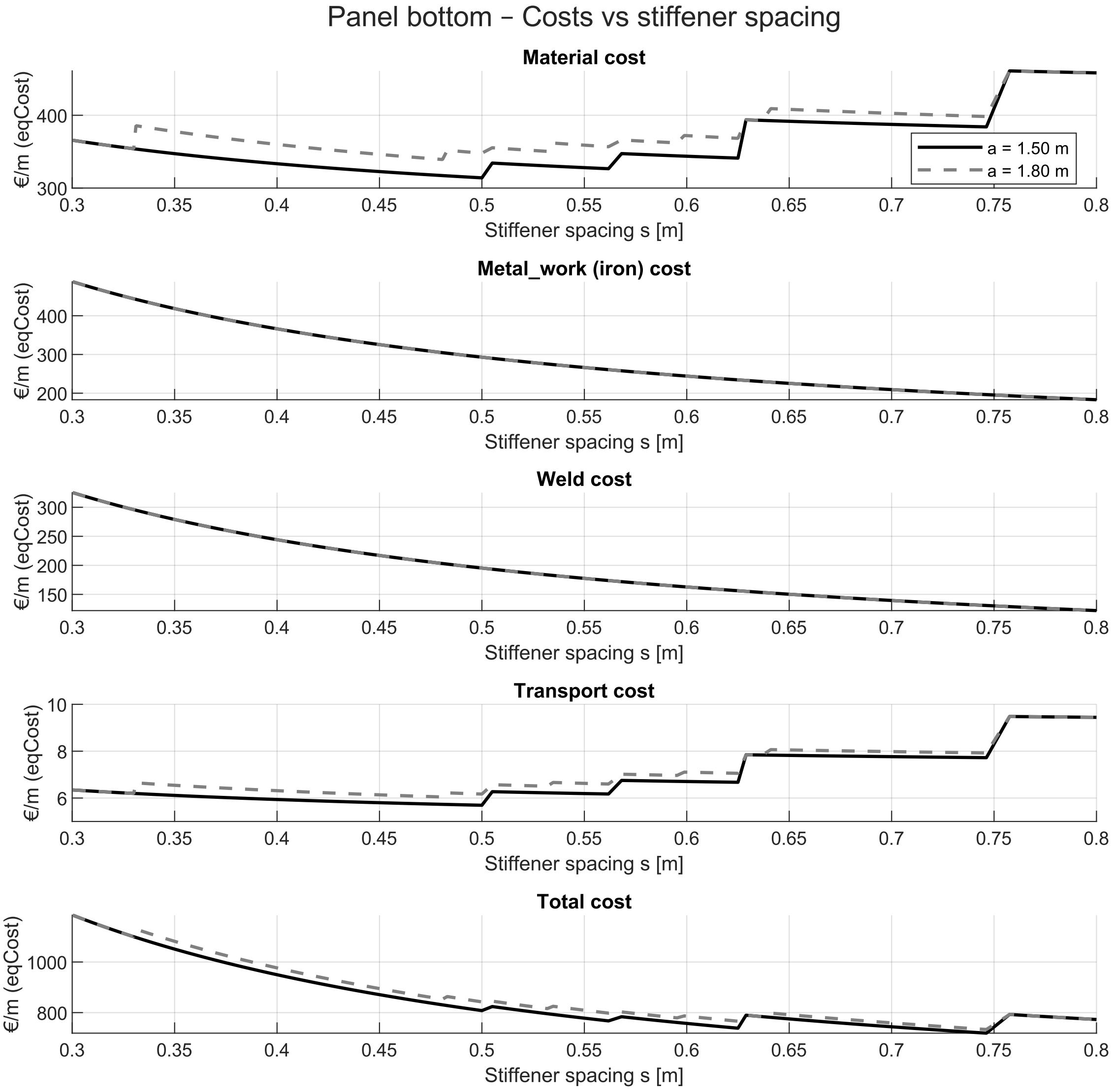


Figure 4.4: Cost breakdown vs stiffener spacing s_{stiff} for bottom shell

Shell below waterline results Figure 4.5 shows the cost evolution for shell plating below the waterline as a function of the stiffener spacing s, for frame spacings of $a = 1.50$ m and $a = 1.80$ m.

Shell below waterline results The shell plating below the waterline follows an almost identical trend to the bottom shell results. This behaviour is a direct consequence of the identical reference panels adopted for both locations, which lead to comparable plate thickness requirements and stiffener section modulus demands.

As a result, the same sequence of discrete plate thickness changes and stiffener profile transitions is observed over the investigated range of stiffener spacing. This implies that the cost-optimal stiffener spacings coincide with those found for the bottom structure, at $s_{\text{stiff}} = 0.625$ m and $s_{\text{stiff}} = 0.746$ m.

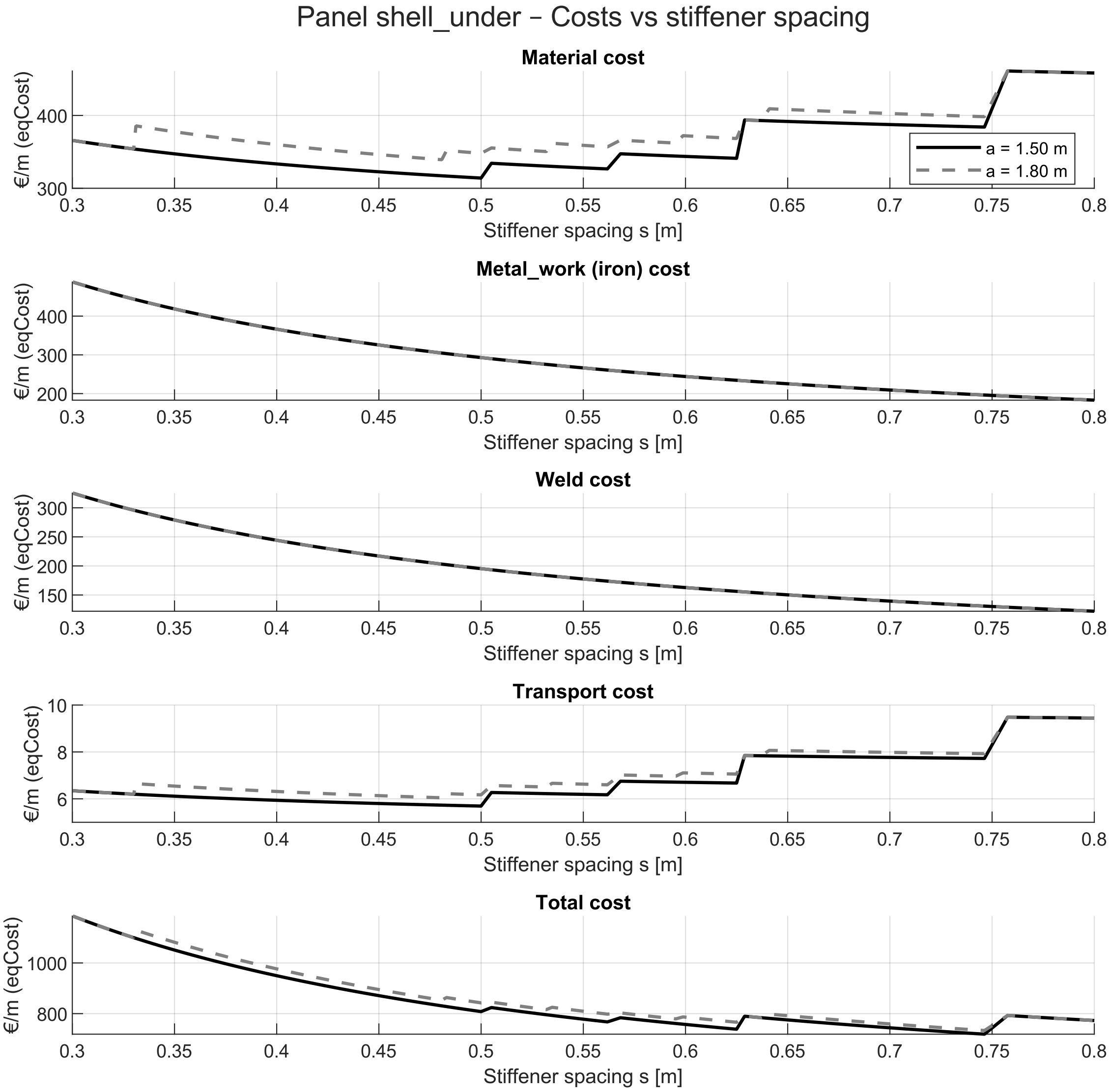


Figure 4.5: Cost breakdown vs stiffener spacing s_{stiff} for shell below waterline

Shell above waterline results Figure 4.6 shows the optimisation results for shell plating above the waterline. The shell plating above the waterline shows a distinctly different behaviour compared to the submerged shell panels. Frequent stepwise increases in plate thickness are observed, which occur at smaller stiffener spacings. This is a direct consequence of the relatively small reference panel and the stricter design requirements at this location, which are primarily driven by cosmetic considerations. As a result, plate thickness increases already occur at $s \approx 0.40\,\text{m}$ and $s \approx 0.50\,\text{m}$. These thickness changes are simultaneously reflected in the welding and metal-work costs through discrete increases in the required weld throat thickness.

An interesting outcome is that the lowest total cost is found at a relatively large stiffener spacing of approximately $s = 0.60\,\text{m}$ and $s = 0.75\,\text{m}$. This indicates that the reference configuration for the shell above the waterline is predominantly labour-cost driven. Such behaviour is consistent with practical design considerations, as aesthetic requirements typically enforce small stiffener spacings, which significantly increase fabrication effort.

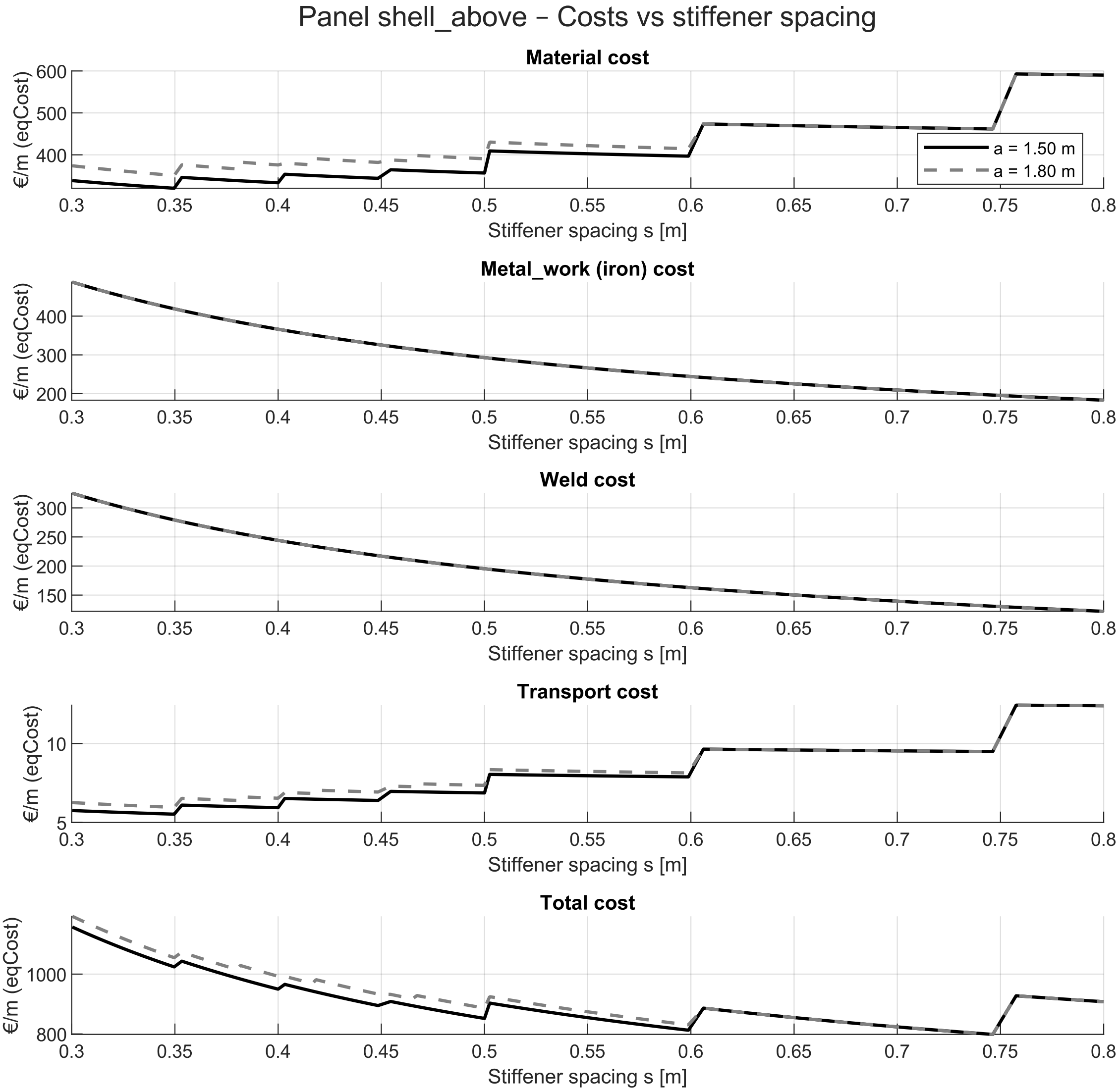


Figure 4.6: Cost breakdown vs stiffener spacing s_{stiff} for shell above waterline

Weather deck results For the weather deck panels, presented in . 4.7, several distinct effects can be observed. A particularly notable feature is observed beyond $s = 0.50\,\text{m}$, corresponding to the reference panel configuration. Contrary to expectation, the material cost decreases for increasing stiffener spacing in this region, despite the increase in plate thickness. This behaviour is caused by the discrete plate pricing used in the cost model, where the price per tonne drops significantly from 1590 €/t for 6 mm plate to 1270 €/t for 7 mm plate. As a consequence, thicker plate material may locally result in lower material costs.

For both frame spacings ($a = 1.50\,\text{m}$ and $a = 1.80\,\text{m}$), small discrete cost increases associated with stiffener profile changes are observed. The combined effect of these mechanisms results in a comparatively smooth total cost curve, with the minimum occurring at the largest stiffener spacing of approximately $s = 0.8\,\text{m}$.

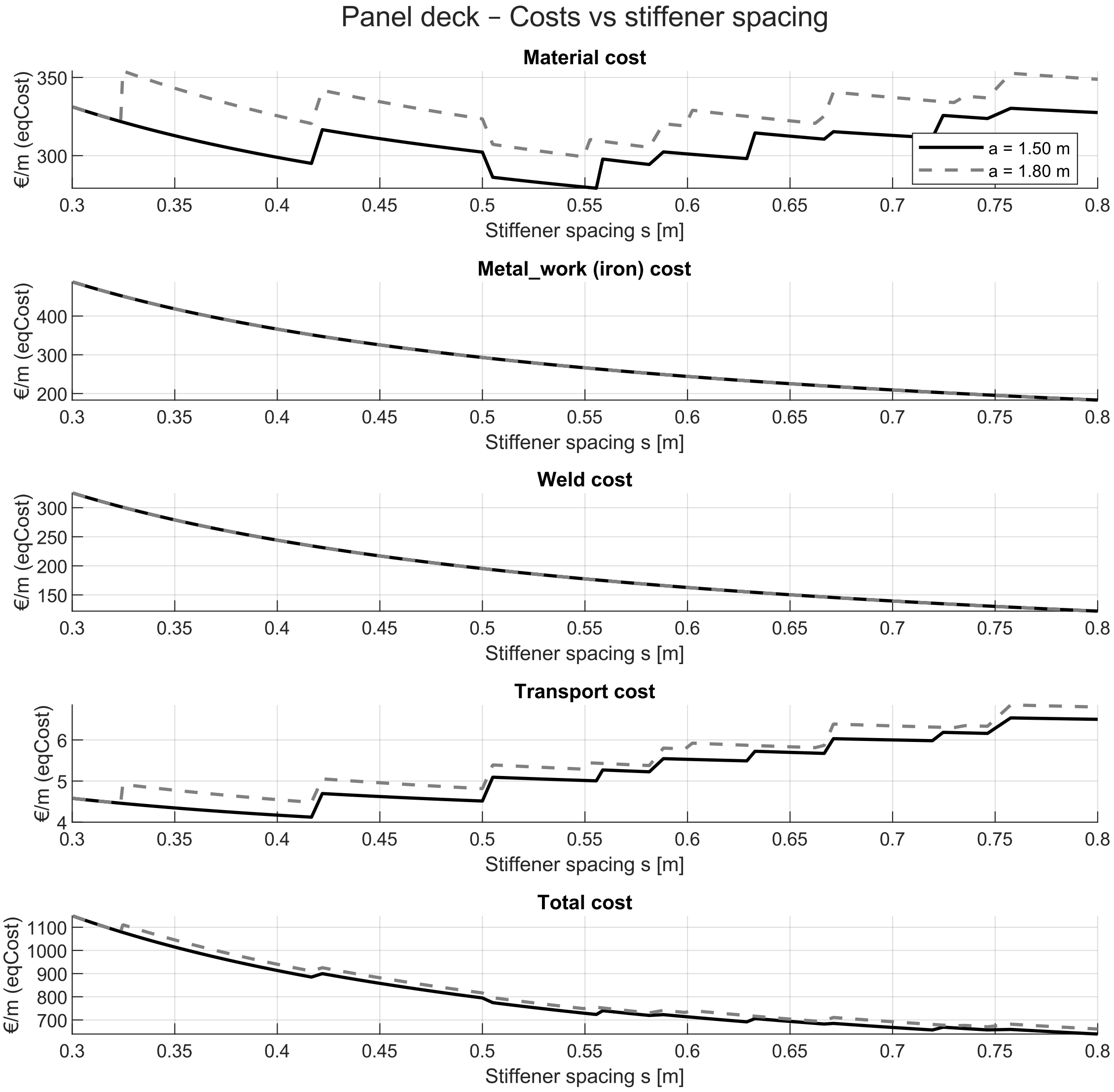


Figure 4.7: Cost breakdown vs stiffener spacing s_{stiff} for weather deck

Tanktop results The tanktop panels exhibit the same behaviour as the weather deck panels, as can be seen in Fig. 4.8. This similarity is a direct consequence of the adopted reference panels, which are identical for both locations and therefore lead to comparable plate thickness requirements and stiffener demands.

As a result, the same mechanisms govern the cost evolution with stiffener spacing, including the availability of thinner plating at smaller spacings, discrete material cost effects caused by non-monotonic plate pricing, and limited stiffener profile transitions. Consequently, the total cost curve shows a similarly smooth shape, and the location of the cost optimum coincides with that of the weather deck configuration.

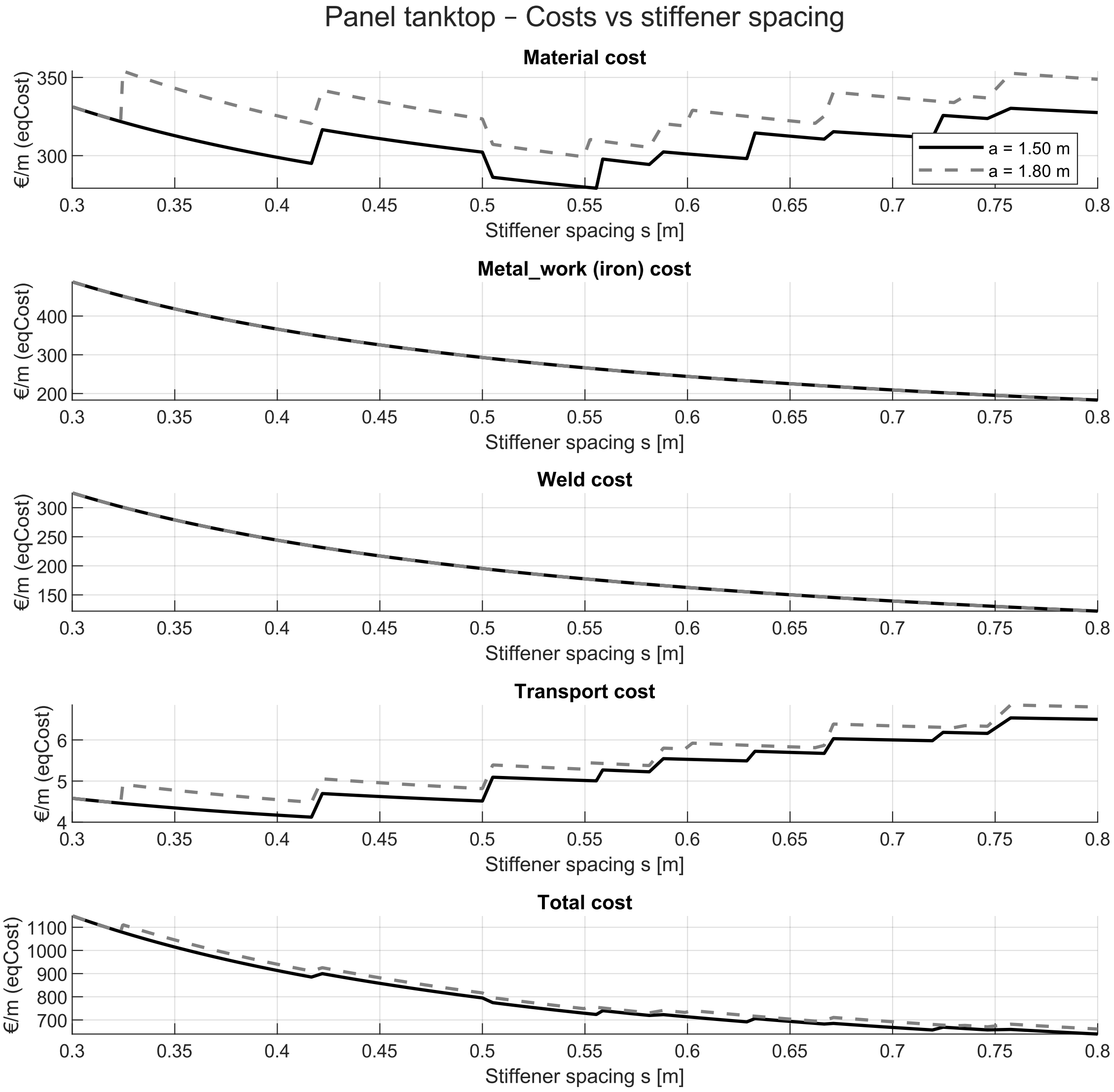


Figure 4.8: Cost breakdown vs stiffener spacing s_{stiff} for tanktop

Inner deck results The inner deck panels show a regular stepwise increase in material cost with increasing stiffener spacing, as shown in fig. 4.9, which is primarily caused by discrete increases in the selected plate thickness. For $a = 1.50\,\text{m}$, material cost increases are observed up to $s_{\text{stiff}} = 0.56\,\text{m}$ due to both plate thickness and stiffener profile changes, followed by a noticeable cost reduction at $s_{\text{stiff}} = 0.60\,\text{m}$. This drop is explained by the lower material price of 7 mm plating compared to 6 mm plating in the adopted cost model. Beyond this point, the cost evolution follows a regular trend without additional irregularities.

For $a = 1.80\,\text{m}$, more frequent stiffener profile transitions are observed, which is attributed to the higher required section modulus resulting from the larger frame spacing. The total cost decreases monotonically with increasing stiffener spacing for both frame spacings, with the minimum total cost occurring at the upper bound of the investigated range, $s_{\text{stiff}} = 0.80\,\text{m}$.

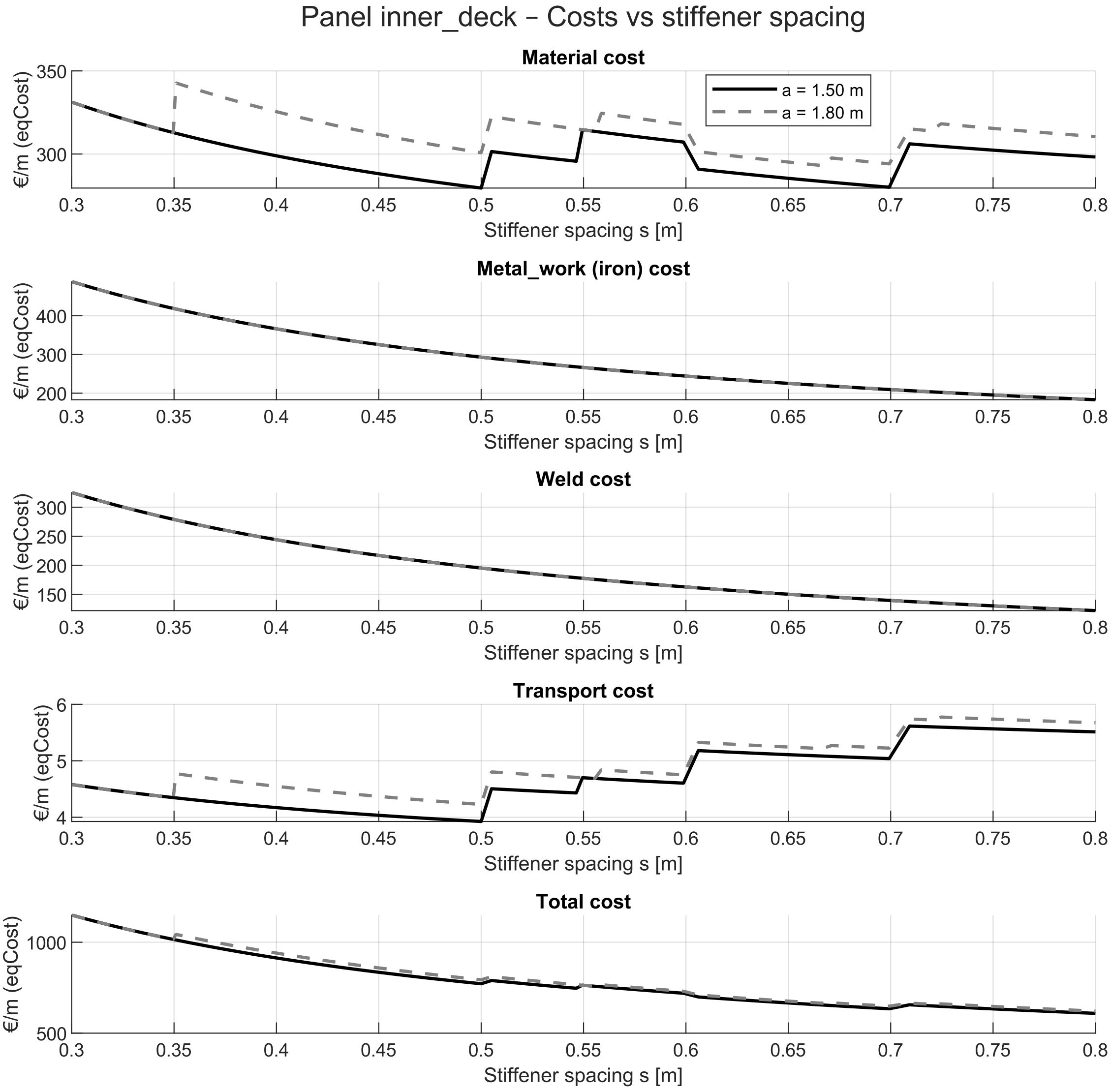


Figure 4.9: Cost breakdown vs stiffener spacing s_{stiff} for inner decks

Conclusions on optimisation results The optimisation results demonstrate that the cost behaviour of longitudinally stiffened panels is governed by a combination of structural demand, production discretisation, and pricing effects. Across all panel types, the total cost evolution is dominated by discrete changes in plate thickness and, for larger frame spacings, by transitions in stiffener profile selection. These discretisation effects lead to stepwise cost trends and local minima that would not be captured by continuous optimisation approaches.

Panels governed by higher external pressures or stricter reference configurations exhibit more frequent plate thickness increases and stiffener transitions, while panels with lower structural demand allow smoother cost reductions with increasing stiffener spacing. In several cases, counter-intuitive cost reductions are observed when thicker plates coincide with lower material prices, highlighting the strong influence of market-based price discretisation.

Overall, the results show that cost-optimal designs are consistently located just before discrete transitions in plate thickness or stiffener profile. This underlines the importance of explicitly accounting for discrete production parameters and realistic cost models when optimising one-off steel structures for minimum construction cost.

For further research, the panel configurations identified in this optimisation study will be evaluated within the FBC model. In this subsequent analysis, all relevant production- and design-related KPIs will be assessed and compared against the optimisation outcomes obtained in the present work.

4.1.4. Quantitative KPI evaluation of LR-optimised panel structures

This subsection evaluates the LR-optimised panel configurations using a set of quantitative key performance indicators (KPIs) that collectively capture buildability, structural efficiency, production complexity, environmental impact, and total production cost. Following the optimisation of scantling configurations with respect to cost, the resulting design space is first screened for practical feasibility using a deformation-based buildability criterion. Subsequently, the remaining feasible configurations are assessed in terms of relative structural mass, number of parts, production lead time, CO2 emissions, and total production cost, each expressed relative to the corresponding yard reference panels. By evaluating these KPIs consistently across all panel types and frame spacings, the analysis provides insight into the trade-offs between structural performance, production effort, and cost efficiency, and allows the identification of robust design trends that support production-oriented decision-making.

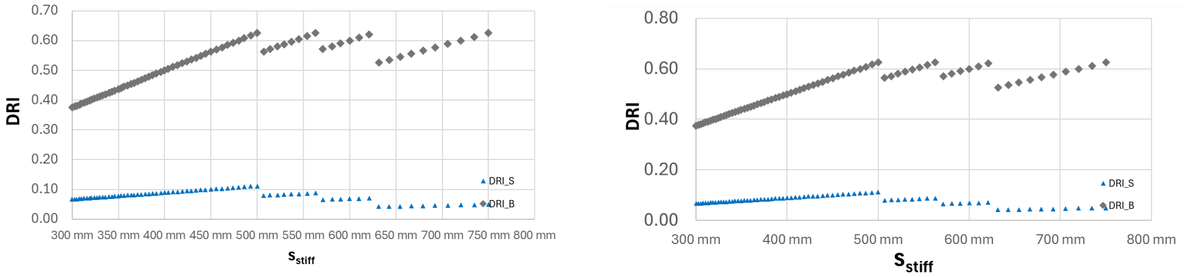
Buildability check – Deformation Risk Index

The buildability of the optimised panel configurations is evaluated using the Deformation Risk Index (DRI), which consists of two independent components. The first component, $\mathrm{DRI_B}$, represents the *slenderness-related deformation risk* and is governed by the plate slenderness parameter β. The second component, $\mathrm{DRI_S}$, represents the *heat-induced deformation severity* and is related to the structural sensitivity to welding-induced thermal loads.

The DRI values presented in Figure 4.10 are evaluated relative to the corrected reference values listed in Table 4.2. Both $\mathrm{DRI_B}$ and $\mathrm{DRI_S}$ are normalised with respect to the corresponding corrected reference limits, such that a value of unity represents the maximum admissible deformation risk for the given panel type. By applying this relative normalisation, the buildability assessment ensures that all optimised configurations remain at least as robust against deformation as their respective reference panels.

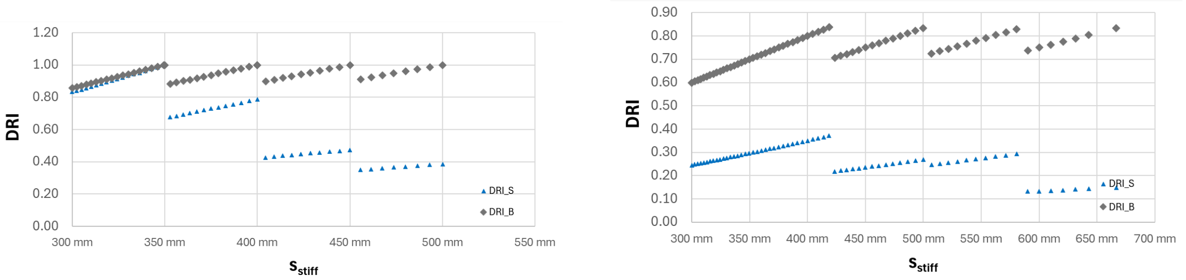
As a consequence, all optimisation results satisfy the DRI-based buildability feasibility check. Although variations in stiffener spacing and plate thickness lead to changes in both slenderness and heat-deformation sensitivity, none of the investigated configurations exceed the corrected reference limits for either $\mathrm{DRI_B}$ or $\mathrm{DRI_S}$. The DRI check therefore serves as a screening criterion rather than a governing constraint in the present optimisation framework.

After applying the deformation-based buildability check, the only remaining feasibility constraint imposed on the optimisation results is a structural mass limit. For all panel types, the total structural mass is restricted to a maximum of 125 % of the mass of the corresponding reference panel configuration, preventing impractical solutions that are formally feasible but disproportionally heavy. These filtered results will be used for further KPI evaluation.



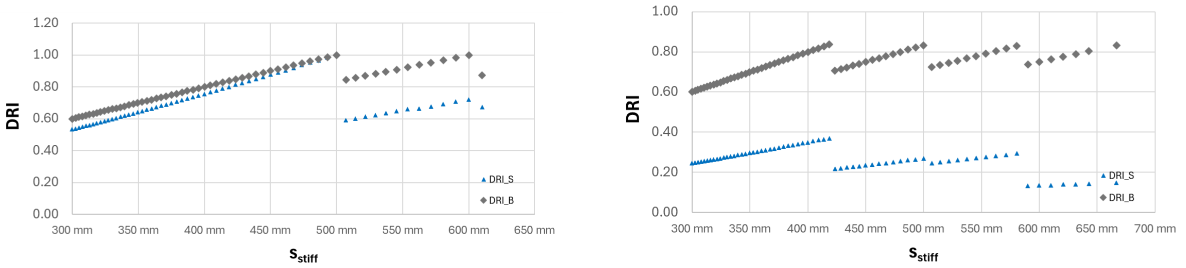
(a) Bottom shell

(b) Shell below waterline



(c) Shell above waterline

(d) Tanktop



(e) Inner decks

(f) Weather deck

Figure 4.10: DRI$_S$ and DRI$_B$ results for all investigated panel types

Relative structural mass

The first key performance indicator evaluated is the relative structural mass with respect to the reference panels used for the cost comparison, as listed in Table 3.8. These reference panels represent the original scantling configurations applied in yachts produced by the yard. Although structural mass is implicitly reflected through part count and component dimensions, it is used explicitly here as a feasibility constraint to exclude excessively heavy panel configurations. As introduced earlier, a maximum allowable mass increase of 25% relative to the reference configuration is enforced.

The mass constraint predominantly affects configurations with the larger frame spacing of $a = 1.80\,\text{m}$, particularly for shell structures above the waterline. For this panel type, all configurations with stiffener spacing $s > s_{\text{ref}}$ at $a = 1.80\,\text{m}$ are excluded due to exceeding the mass limit. In addition, for shell-above-waterline panels with $a = 1.50\,\text{m}$, feasible solutions are restricted to stiffener spacings $s \leq 0.50\,\text{m}$.

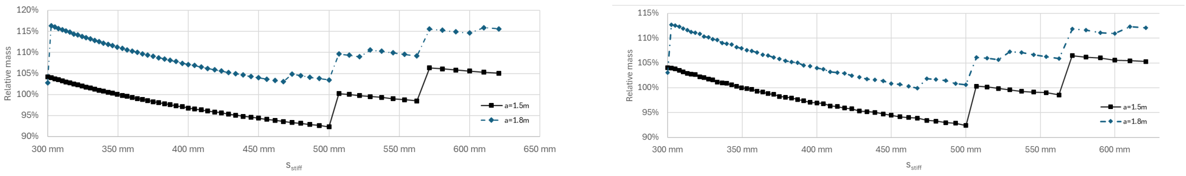
For tanktop and weather deck structures, the mass constraint limits the $a = 1.80\,\text{m}$ configurations to stiffener spacings up to approximately $s = 0.63\,\text{m}$. This indicates that, when the same Feature-Based Costing rules are applied, similar trends are observed for panel types with comparable reference configurations. A comparable behaviour can also be identified for the shell below the waterline and bottom shell structures.

For the remaining panel types, the mass constraint only becomes active at relatively large stiffener spacings, typically between $s = 0.60\,\text{m}$ and $s = 0.65\,\text{m}$. Within these bounds, the majority of configurations remain feasible, indicating that the design space still offers sufficient viable alternatives within the imposed feasibility limits.

A further observation concerns the stepwise nature of the relative mass curves, which results from the discrete selection of available plate thicknesses and stiffener profiles. Larger steps are associated with increases in plate thickness, while smaller steps correspond to the selection of larger HP stiffener profiles. In general, configurations with a frame spacing of $a = 1.50\,\text{m}$ are significantly lighter than those with $a = 1.80\,\text{m}$.

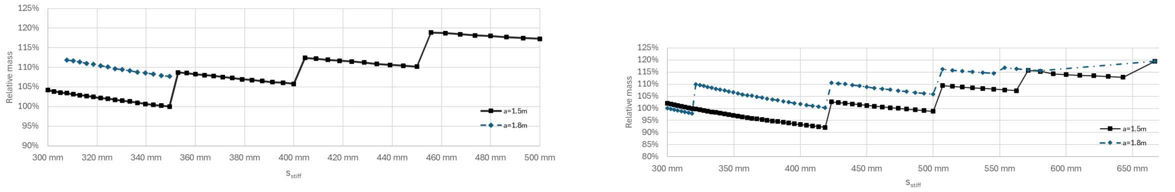
Only in regions of the design space where a minimum plate thickness is enforced, or where no thinner plate options are available (with 5 mm being the minimum modelled thickness), can configurations with $a = 1.80\,\text{m}$ become lighter than their $a = 1.50\,\text{m}$ counterparts. This behaviour is observed consistently across all panel types, with the exception of the shell above the waterline.

In most cases, local minima in structural mass are found close to the strength reference configurations. Notable exceptions are the tanktop and weather deck panels, for which the reference configurations do not correspond to the lightest feasible solutions. This can be explained by the absence of a minimum plate thickness requirement for these panel types, combined with the fact that the reference panels do not make use of the minimum available plate thickness.



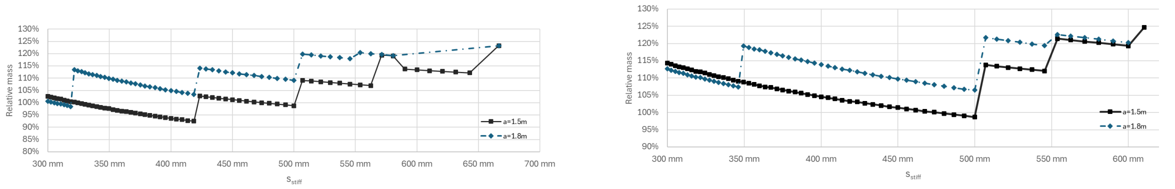
(a) Bottom shell

(b) Shell below waterline



(c) Shell above waterline

(d) Weather deck



(e) Tanktop

(f) Inner decks

Figure 4.11: Relative structural mass as a function of stiffener spacing for all panel types.

Relative number of parts

As discussed in Section 3.3, part count reduction is identified as the primary driver for cost reduction, both in absolute terms (as will be demonstrated in Section 4.1.4) and from a process-efficiency perspective. Although the influence of part count reduction on all downstream KPIs is not quantified explicitly within this thesis, its impact on production effort, lead time, and overall build complexity is substantial and should not be underestimated.

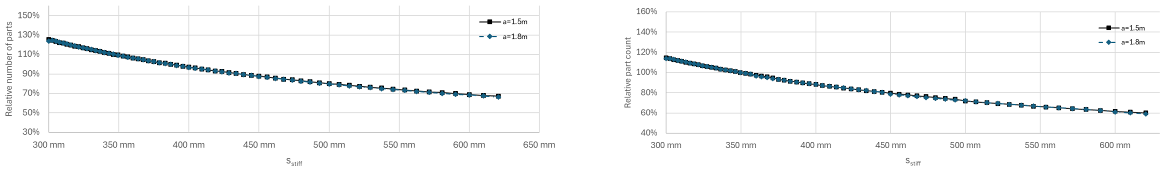
Figure 4.12 shows the relative number of parts as a function of stiffener spacing for all considered panel types. For all panels, a clear decreasing trend can be observed with increasing stiffener spacing, reflecting the direct reduction in the number ofprimary, secondary and tertiary components. The most significant reductions occur for panel types that require buckling strips up to a certain plate thickness. Once these buckling strips are no longer required, a stepwise decrease in total part count is observed. This is a key observation, as the elimination of buckling strips effectively doubles the achievable part count reduction within a relatively small increase in stiffener spacing.

For the shell above the waterline, the relative part count at $a = 1.5\,\text{m}$ decreases from approximately 88%

to 48%, corresponding to an additional reduction of roughly 40%. For the weather deck and tanktop panels, an even larger reduction is observed, from approximately 82% to around 30%. This highlights the dominant contribution of buckling-related detailing to overall structural complexity.

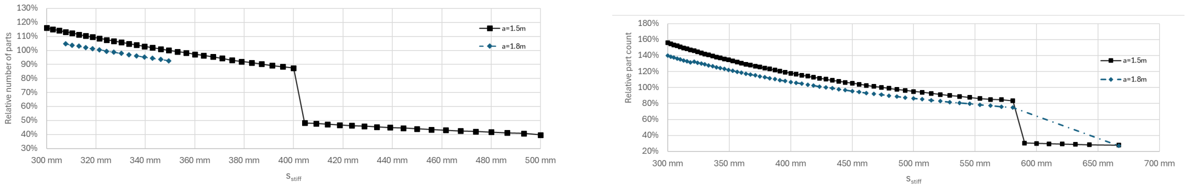
In addition to plate-related effects, the influence of stiffener size on part count is clearly visible. As stiffener height increases, a height-stacking effect occurs, leading to the introduction of additional components and, consequently, a local increase in part count. This behaviour is most clearly illustrated by the inner deck results shown in Figure 4.12f, where a small step increase in part count is observed at $s = 0.35\,\mathrm{m}$ for $a = 1.8\,\mathrm{m}$. Similar effects can be identified for the inner deck at $a = 1.5\,\mathrm{m}$ just beyond $s = 0.55\,\mathrm{m}$, as well as for the tanktop and weather deck panels around $s = 0.325\,\mathrm{m}$. These observations demonstrate that increases in stiffener dimensions have a direct and unfavourable impact on part count and, by extension, on all dependent KPIs such as structural mass, production lead time, CO2 emissions, and ultimately total production cost.

An additional effect, which is not explicitly quantified within this thesis, is the increase in gross tonnage (GT) resulting from height-stacking effects associated with larger stiffener profiles. As the vessels considered in this study are predominantly designed to maximise interior volume, increases in stiffener height directly reduce the available internal space and therefore lead to higher gross tonnage. This further reinforces the importance of limiting stiffener dimensions from both a production and a naval architectural perspective.



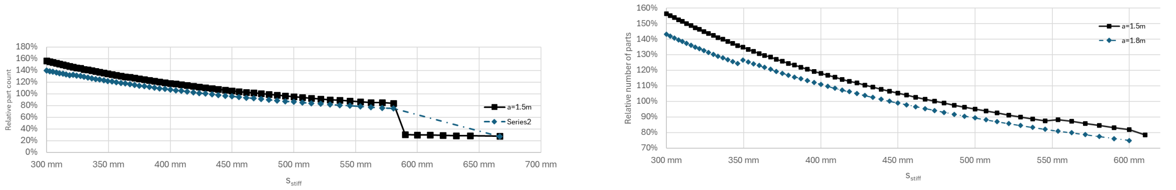
(a) Bottom shell

(b) Shell below waterline



(c) Shell above waterline

(d) Weather deck



(e) Tanktop

(f) Inner decks

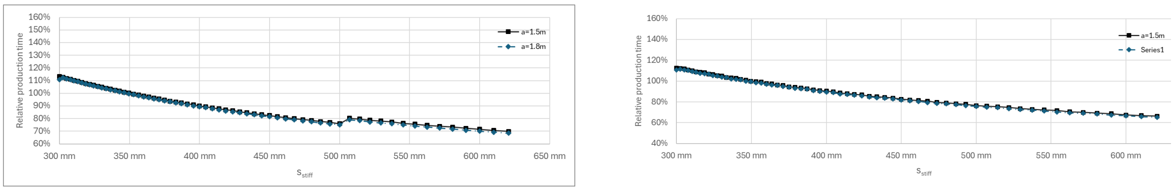
Figure 4.12: Relative part count relations for all panel types.

Relative production lead time

The results for relative production lead time exhibit the same overall trends as those observed for the relative number of parts, across all panel types and frame spacings. This behaviour is expected, as the lead time model applied in this study is feature-based and directly linked to the number of structural parts and the associated assembly operations. As a result, reductions in part count are translated almost directly into reductions in production lead time.

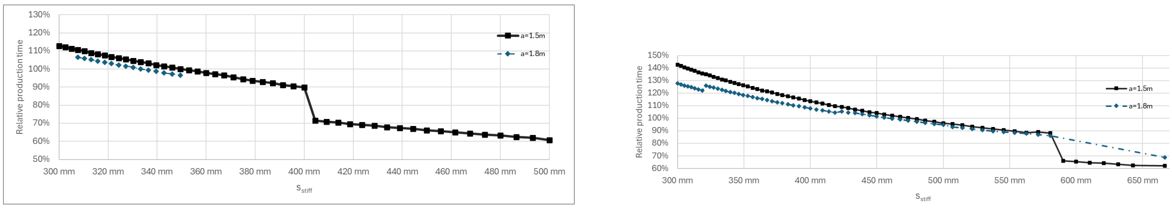
With increasing stiffener spacing, the production lead time decreases monotonically, while discrete step changes occur at the same locations as identified in the part count results. These step changes are associated either with the removal of secondary structural elements, such as buckling strips, or with increases in stiffener size that introduce additional fabrication complexity. Panel types for which buckling strips are eliminated within the investigated spacing range show the most pronounced reductions in production lead time, reflecting the significant decrease in assembly effort.

The close correspondence between the part count and production lead time trends confirms that production lead time in steel hull fabrication is predominantly governed by structural complexity rather than by material volume alone. This observation further reinforces the importance of part count reduction as a primary Design for Production objective, as improvements in this metric directly propagate to shorter assembly times and reduced overall production lead time.



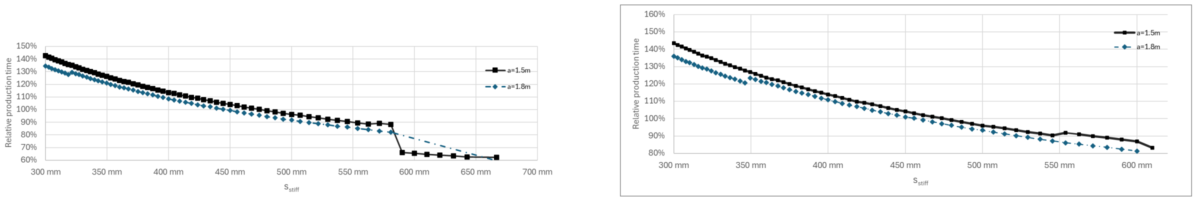
(a) Bottom shell

(b) Shell below waterline



(c) Shell above waterline

(d) Weather deck



(e) Tanktop

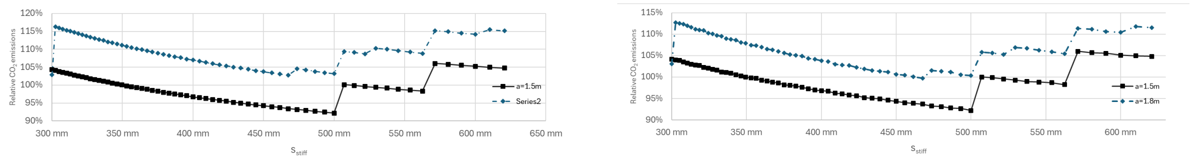
(f) Inner decks

Figure 4.13: Relative production lead time relations for all panel types.

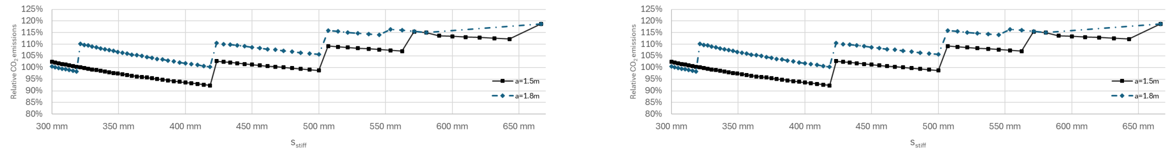
Relative CO2 emissions

The relative CO2 emission results closely follow the trends observed for relative structural mass across all panel types and frame spacings. This behaviour is a direct consequence of the emission model adopted in this study, in which emissions associated with steel production dominate the total CO2 footprint, while welding-related emissions are negligible in comparison. As a result, variations in plate thickness and stiffener size, which primarily govern structural mass, also determine the relative CO2 emissions.

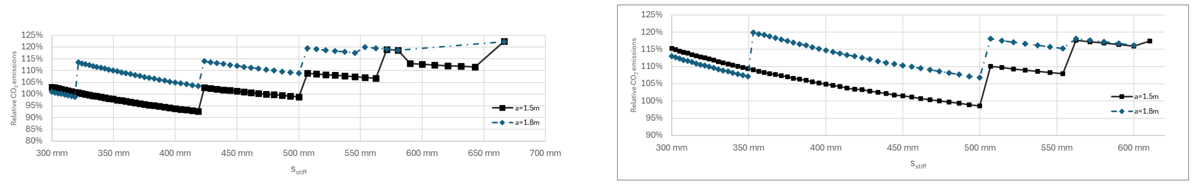
The stepwise nature of the CO2 curves therefore reflects the discrete selection of available plate thicknesses and stiffener profiles. Larger steps correspond to increases in plate thickness, whereas smaller steps originate from transitions to larger HP stiffener profiles. No additional trends are introduced by fabrication-related processes, and the CO2 evaluation does not reveal deviations from the mass-based behaviour discussed earlier.



(a) Bottom shell **(b)** Shell below waterline



(c) Shell above waterline **(d)** Weather deck



(e) Tanktop **(f)** Inner decks

Figure 4.14: Relative CO$_2$ emissions as a function of stiffener spacing for all panel types.

The KPI analysis demonstrates that increasing stiffener spacing reduces part count and weld length, but simultaneously induces higher plate thicknesses, larger stiffener profiles, and height-stacking effects. As a result, improvements in individual production indicators do not necessarily translate into overall structural simplification.

Since these KPIs interact in opposing directions, their net effect cannot be assessed intuitively. A consolidated economic evaluation is therefore required to determine whether the observed structural trade-offs ultimately lead to cost savings or cost increases. The following section translates the KPI trends into relative production costs and evaluates their combined impact.

Relative costs

The previously presented KPIs quantified how variations in stiffener spacing and frame spacing affect structural mass, weld length, distortion risk and part count within the admissible design space. While these indicators provide insight into structural complexity and production effort, their combined economic impact remains to be assessed.

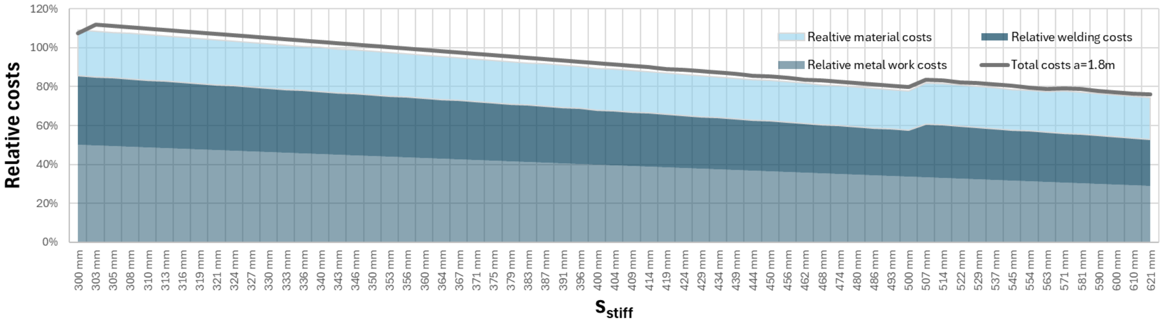
The following section therefore translates the observed KPI trends into relative production costs. By evaluating the aggregated cost components for each configuration, the economic consequences of structural simplification and height-stacking effects can be interpreted in a consistent manner.

Interpretation of relative cost results for shell panels Across all shell panel types, Figure 4.15 shows configurations with a frame spacing of $a = 1.80\,\mathrm{m}$ generally exhibit slightly higher total production costs than those with $a = 1.50\,\mathrm{m}$, while following an almost identical cost trend as a function of stiffener spacing. This indicates that the cost savings associated with a reduced number of stiffeners at larger frame spacings are largely counterbalanced by the need for heavier stiffener profiles and increased plate thickness. In addition, larger stiffener heights introduce height-stacking effects, which further reduce the economic benefit of increased frame spacing. As a result, increasing the frame spacing does not lead to a proportional reduction in total production cost.

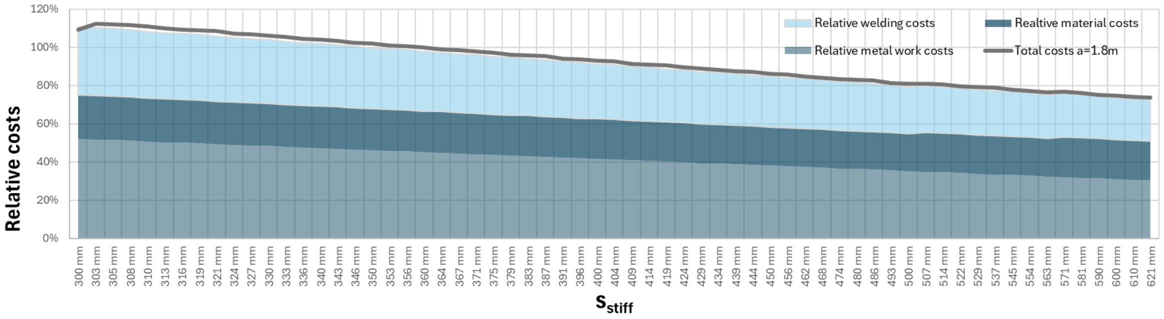
A pronounced increase in welding costs is observed for both the bottom shell and the shell below the waterline. This increase coincides with a discrete rise in the required weld throat thickness, driven by the selection of thicker plate material. Since welding and metalwork costs are directly linked to weld geometry in the applied cost model, this transition is clearly reflected in the cost breakdown.

For the shell above the waterline, configurations with $a = 1.80\,\text{m}$ only yield feasible solutions for relatively small stiffener spacings ($s < 0.34\,\text{m}$). This behaviour is consistent with the stricter structural and cosmetic requirements applied to this panel type, which significantly constrain the feasible design space when larger framespacings are adopted.

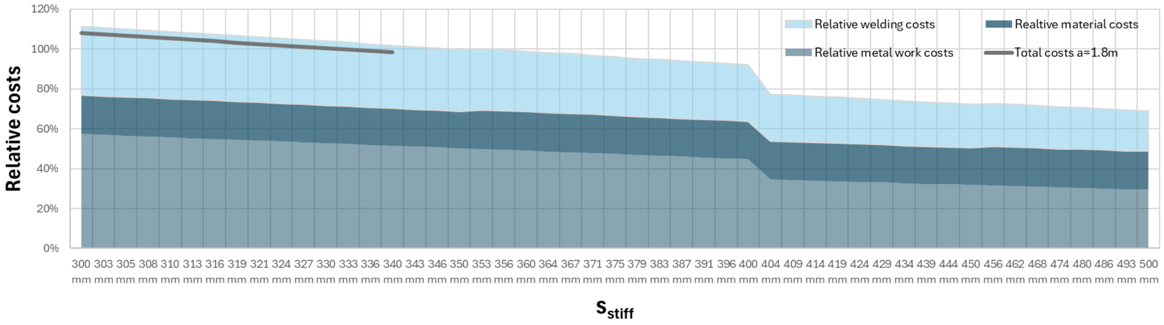
Two distinct cost transitions can be identified for the shell above the waterline. A moderate increase in total cost occurs just beyond $s = 0.35\,\text{m}$, resulting from an increase in the selected plate thickness. A more pronounced decrease in total cost is observed beyond $s = 0.40\,\text{m}$, where buckling strips are no longer required. The removal of these secondary structural elements leads to a substantial reduction in metalwork costs. At the same time, welding costs increase due to the selection of a thicker (9 mm) plate, partially offsetting this reduction. Nevertheless, the overall effect remains a net decrease in total cost.



(a) Bottom shell



(b) Shell below waterline



(c) Shell above waterline

Figure 4.15: Relative cost build-up as a function of stiffener spacing for all shell panel types, evaluated for $a = 1.50\,\text{m}$ and $a = 1.80\,\text{m}$.

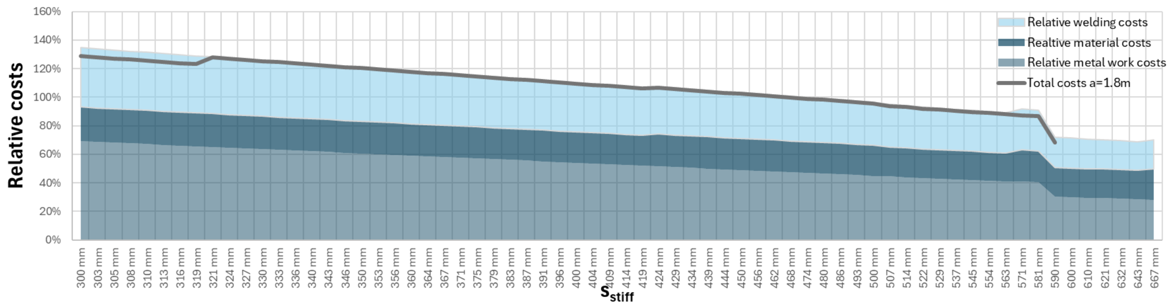
Interpretation of relative cost results for deck structures Figure 4.16presents the relative cost build-up for tanktop, weather deck, and inner deck panels as a function of stiffener spacing. For all deck structures, configurations with a frame spacing of $a = 1.80\,\text{m}$ are initially slightly cheaper than those with $a = 1.50\,\text{m}$ at small stiffener spacings. This behaviour is explained by the minimum plate thickness of 5 mm imposed in the model: for small values of s, both frame spacings are governed by the same minimum plate thickness, while the reduced number of stiffeners at $a = 1.80\,\mathrm{m}$ directly lowers part count and associated production costs.

Over the majority of the investigated stiffener spacing range, the total production costs for $a = 1.50\,\mathrm{m}$ and $a = 1.80\,\mathrm{m}$ remain very close and follow an almost identical trend. This indicates that the cost reductions achieved through part count reduction at larger frame spacings are largely offset by the requirement for heavier stiffener profiles and increased plate thickness. As a result, these opposing effects nearly cancel each other out.

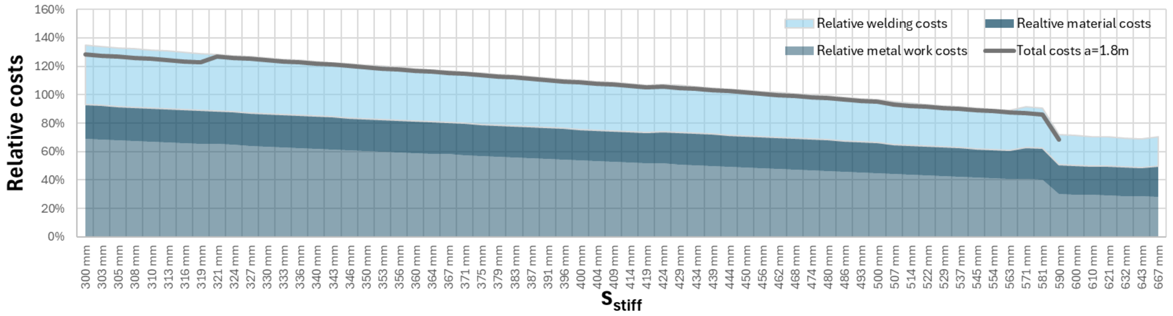
At larger stiffener spacings, the cost advantage of $a = 1.80\,\mathrm{m}$ becomes more pronounced. This occurs once both frame spacings require the same stiffener profile (HP100×6), after which the continued reduction in part count for $a = 1.80\,\mathrm{m}$ becomes the dominant factor. In this region of the design space, the larger frame spacing leads to lower total production costs, confirming that part count reduction regains its influence once the governing structural requirements converge.

For the weather deck and tanktop panels, a distinct reduction in metalwork costs is observed for stiffener spacings $s \gtrsim 0.59\,\mathrm{m}$. This reduction is caused by the elimination of buckling plates when the governing plate thickness increases to 8 mm. Although this transition coincides with a moderate increase in welding costs due to the thicker plate, the significant decrease in metalwork effort results in a net reduction in total cost.

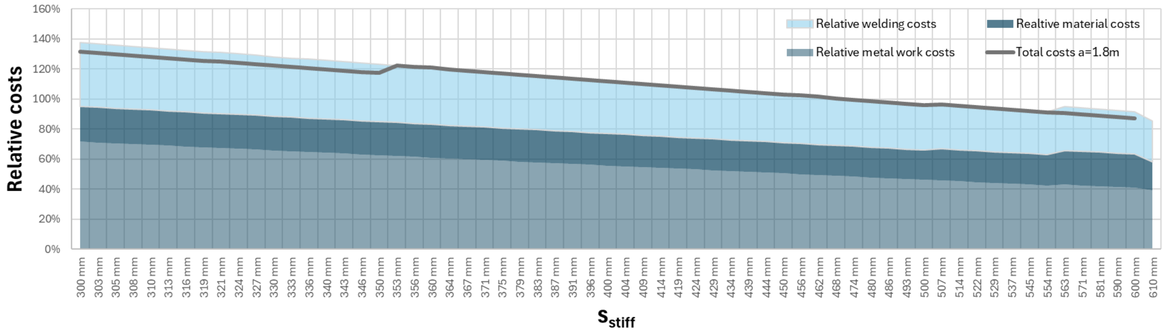
Overall, the results demonstrate that increasing stiffener spacing generally leads to lower production costs, with the most substantial cost reductions occurring when the number of structural parts is significantly reduced. While local increases in plate thickness and stiffener size lead to higher material and welding costs, these effects are outweighed by the elimination of secondary structural components and the associated reduction in assembly complexity. Consequently, part count emerges as the dominant cost driver in the optimisation of deck structures, reinforcing the central role of Design for Production principles in production-oriented scantling optimisation.



(a) Weather deck



(b) Tanktop



(c) Inner decks

Figure 4.16: Relative cost build-up as a function of stiffener spacing for all deck panel types, evaluated for $a = 1.50\,\mathrm{m}$ and $a = 1.80\,\mathrm{m}$.

Taken together, the quantitative KPI evaluation demonstrates that the LR-optimised panel configurations exhibit consistent and physically meaningful trends across all investigated performance indicators. While local increases in plate thickness or stiffener size lead to stepwise changes in mass, emissions, and cost, the dominant effect of increasing stiffener spacing is a systematic reduction in structural complexity. This reduction propagates through part count, production lead time, and ultimately total production cost, confirming that Design for Production-driven optimisation primarily acts on the organisation and efficiency of the manufacturing process rather than on material savings alone. At the same time, the quantitative results highlight that cost-optimal solutions are not uniquely defined, but instead exist within bounded regions of the design space that must be interpreted in relation to feasibility constraints, mass limits, and yard-specific design practices.

While the quantitative KPIs provide objective and comparable measures of performance, they do not fully capture the broader implications of the optimisation results for production processes, organisational readiness, product quality, and brand perception. To address these aspects, the following subsection complements the numerical evaluation with a qualitative assessment, focusing on the implications of the identified design trends for process behaviour, implementation readiness, perceived product quality, and alignment with the shipyard's brand values.

4.1.5. Qualitative KPI evaluation

The quantitative KPI evaluation provides objective insight into the effects of LR-based scantling optimisation on cost, structural mass, production lead time, and environmental impact. However, these numerical indicators do not fully capture the broader implications of the optimisation results for the shipyard context, where production processes, organisational structures, product quality, and brand positioning play an equally important role in design decision-making. To address these aspects, this subsection presents a qualitative evaluation of the optimised panel configurations, focusing on how the identified quantitative trends translate into practical process behaviour, implementation feasibility, and strategic considerations at yard level. By interpreting the optimisation results through a qualitative lens, the analysis complements the numerical KPIs and provides a more holistic assessment of the suitability of Design for Production-driven scantling optimisation within a one-off superyacht production environment.

Process influence

The quantitative KPI relations deal mostly with cost, mass, lead time, and emissions, nevertheless they explain the detailed and transparent influence of the examined design choices in the shipyard production process. Across all KPIs, consistent trends can be found showing that the process-related effect of increased stiffener spacing is reduced structural complexity.

First, the high relation between the part count and the relative production lead time shows that the production process is highly sensitive to the number of individual structural elements. The reduction in stiffener count, as well as removal of tertiary elements such as buckling strips simplify the assembly sequence and reduce weld length. This results in reduced processing, placement, and welding in panels for optimal operational flow.

Second, the stepwise behaviour observed in several KPIs illustrates the deterministic nature of production constraints. Shift in plate thickness, shifts in stiffener profiles and expansion of weld throat size results in local increases in fabrication effort, causing a transient interruption of process flow. However, as a rule of thumb, these local effects are generally overshadowed due to the reduction in overall assembly complexity which was obtained at larger stiffener spacings.

Third, the near symmetric trends for relative lead time and part count verify that the resulting feature-based production method is mainly process-oriented rather than material-oriented. This can be taken to mean that the productivity gains in production efficiency are generally obtained by making the overall operation easier at an organisational level, and not by little decreases in the time it takes to carry out specific assemblages.

Finally, the trade-off between heavy individual components and small total parts means that the emphasis on processes does change. Larger stiffeners and thicker plates might result in bigger demands on handling per component (which are not explicitly shown in this work), but reduced number of components reduces work-related coordination, welding preparations, inspection load, and rework sensitivity. This tendency favours overall simplicity and part number over reduction of single operation, such as local weld length minimization from a process perspective.

Overall, the quantitatively oriented KPI relations show that Design for Production-driven scantling optimisation increases the efficiency of the manufacturing process primarily because of the reduction in structural complexity, the stabilisation of the workflow, and resistance to blockages in assembly, rather than due to the gradual enhancements to individual work in the manufacturing process.

Knowledge and implementation readiness

From a knowledge perspective, the shipyard can be considered fully capable of implementing the findings of this research. The applied Design for Production principles and the underlying cost and process drivers fall well within existing engineering and production expertise. No new materials, construction methods, or fabrication technologies are required.

The primary challenge for implementation does not lie in production capability, but in the structure of the design system. Over time, structural design, outfitting, and production processes have become strongly aligned around a generic frame spacing. This standardisation has resulted in a highly integrated and robust design workflow, reducing engineering effort and coordination risk across disciplines.

Introducing alternative frame spacings, as suggested by the quantitative KPI relations, creates system-level implications rather than isolated structural challenges. Changes in frame spacing affect not only the hull structure, but also downstream design elements such as outfitting supports, system routing, and accommodation interfaces. Consequently, the implementation effort is primarily organisational and architectural in nature rather than purely technical.

At the same time, increased frame spacing generally provides more open space within the structural grid. This can facilitate outfitting activities, as fewer structural members obstruct the installation of systems and components.

The shipyard can therefore be regarded as knowledge-ready, but only partially system-ready. Successful implementation would require either a controlled decoupling of structural design decisions from fixed reference spacings or the development of multiple standardised frame-spacing families. This indicates that the main barrier to implementation is design integration complexity, rather than a lack of technical capability.

Impact on product quality

From a structural integrity perspective, the proposed optimisation results do not adversely affect product quality. All panel configurations are verified against Lloyd's Register requirements, buckling criteria, and deformation risk indicators, ensuring that strength, stiffness, and fabrication-induced deformation remain within acceptable limits. Structural performance is therefore explicitly safeguarded within the applied methodology.

Within the shipyard context, product quality extends beyond structural performance and includes aspects such as predictability, repeatability, and consistent integration of structure, outfitting, and accommodation. Historically, these aspects have been supported through the use of a generic frame spacing, which limits design variation and simplifies coordination between engineering disciplines.

The introduction of alternative frame spacings does not inherently reduce product quality, but it does alter the way quality must be managed. A change in structural configurations places higher demands on design coordination, interface control, and configuration management, particularly at the interfaces between hull structure and outfitting systems. If not properly embedded within the design process, this increased variation may raise the risk of inconsistencies, even when the structural solutions themselves are technically sound.

As a result, the impact of Design for Production optimisation on product quality is primarily organisational rather than technical. Maintaining the current quality level requires that structural optimisation is implemented within a controlled design framework, in which variations in frame spacing are explicitly addressed across all relevant disciplines. When such integration is ensured, the proposed optimisation measures can be adopted without compromising the high and consistent product quality characteristic of the yard.

Impact on brand image

The implementation of Design for Production–driven scantling optimisation may also influence the brand image of the shipyard. For a yard such as Feadship, brand value is closely associated with exclusivity, craftsmanship, and the efficient use of gross tonnage to maximise high-quality interior space. Any production-oriented optimisation strategy must therefore remain compatible with these brand-defining attributes.

From a positive perspective, several outcomes of the optimisation align well with the existing brand positioning. The reduction in part count and the simplification of structural layouts support more robust and controlled production processes, which indirectly reinforce perceptions of craftsmanship, reliability, and technical maturity. These effects strengthen the brand narrative of precision-built, high-quality yachts rather than cost-driven standardisation.

Potential risks to brand image arise primarily from configurations that lead to increases in structural mass or stiffener height. Increases in mass may affect performance, fuel consumption, and cost of ownership, while increases in stiffener height can influence gross tonnage through height-stacking effects or reduced interior design flexibility. As low gross tonnage combined with maximum usable interior volume is a key selling point, such effects must be carefully managed.

It is therefore essential that production-driven efficiency gains are not pursued in isolation. Optimisation solutions that reduce fabrication effort but negatively affect gross tonnage efficiency or spatial quality may conflict with client expectations and the yard's premium positioning. The optimisation framework presented in this research explicitly supports informed trade-offs rather than prescribing a single optimal solution, allowing the shipyard to balance production efficiency with brand-critical design considerations.

Overall, the results indicate that Design for Production optimisation can be implemented without compromising brand image, provided that structural mass growth, stiffener height, and gross tonnage implications are treated as governing constraints during design decision-making. The primary challenge lies not in production capability, but in aligning production-oriented design choices with the brand's core values of exclusivity, spatial efficiency, and long-term value.

The qualitative evaluation confirms that the trends identified in the quantitative KPI analysis are not only numerically favourable, but also align well with practical considerations related to production processes, organisational readiness, product quality, and brand positioning. The dominant effect of reduced structural complexity, achieved through increased stiffener spacing and the elimination of secondary elements, translates into more robust and predictable production workflows without compromising structural integrity or perceived quality. At the same time, the analysis highlights that successful implementation depends primarily on design integration and system-level coordination rather than on technical feasibility alone.

Taken together, the quantitative and qualitative evaluations demonstrate that no single configuration can be identified as universally optimal across all criteria. Instead, a bounded region of feasible and production-efficient solutions emerges, within which trade-offs between cost, mass, process simplicity, and design integration must be made explicitly. These findings indicate that Design for Production-driven optimisation is most effective when used as a decision-support tool rather than as a prescriptive design rule.

Based on this combined assessment, the following section synthesises the optimisation results into a set of recommended scantling configurations. These recommendations aim to balance production efficiency, structural performance, and integration robustness, providing practical guidance for the selection of frame spacing and stiffener arrangements that can be adopted within the shipyard's existing design and production framework.

4.2. Recommendation of Scantling Choice Implementation

The primary objective of this research was to identify and evaluate practically implementable design measures capable of achieving a reduction in total steel hull production cost in the order of 10–15%, without compromising structural integrity, classification compliance, or production robustness. This section translates the analytical and optimisation results of the study into a concrete, short-term implementable recommendation for scantling selection.

The proposed implementation strategy is deliberately conservative and focuses on configurations that are already rule-compliant, largely structurally validated, and closely aligned with current shipyard practice. As such, the recommendations presented here are intended to serve as a realistic baseline for short-term application in a one-off superyacht production environment. This section discusses the reasoning behind the recommendations, the related relative KPI scores, and the calculated cost reduction.

4.2.1. Recommended configuration

As discussed earlier, clear distinctions exists between the *as-built* configurations and the *strength-optimal* configurations. The recommended scantlings therefore primarily refer to the strength reference panels used in the structural verification, with the exception of the shell above the waterline (Shell AW). These reference panels are aligned with Lloyd's Register requirements and demonstrate measurable reductions in production cost and, where applicable, structural mass when compared to the current cost reference (*as-is*) design. Figure 4.17 presents the summed relative total cost, mass and lead time of all panels excluding shell above the waterline at a web frame spacing of $a = 1.8m$.

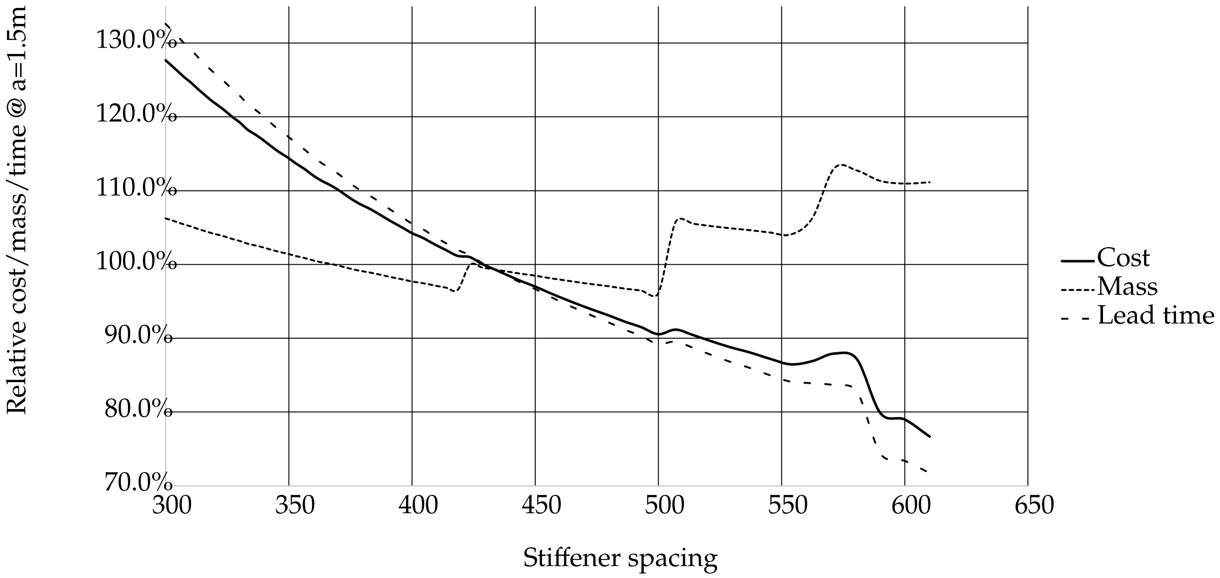


Figure 4.17: Summed KPIs for all panels except shel AW

The shell above the waterline is subject to additional cosmetic constraints, which limit the range of acceptable scantling configurations. Paradoxically, these constraints make the Shell AW particularly sensitive to cost reduction when operating close to the imposed limits. Specifically, the limitation on stiffener spacing, defined as $s_{\text{stiff}} \leq 50\,t_{\text{plate}}$, allows for relatively large proportional increases in stiffener spacing when the plate thickness is increased. This mechanism explains the pronounced cost reduction potential observed for the Shell AW configuration despite its geometric and aesthetic constraints.

Relative to the cost reference panels representing the current *as-is* design, the strength reference panels consistently:

- reduce total production cost,
- limit increases in structural mass and CO_2 emissions,
- maintain full compliance with classification society rules and shipyard standards.

Importantly, these improvements are achieved without introducing unconventional scantling values or deviating from established structural design philosophy. Consequently, the strength reference panels provide a robust and low-risk baseline for practical implementation in a one-off superyacht production environment.

In addition, a certain degree of standardisation between panel types is deliberately maintained. This approach ensures process simplicity for both engineering and production activities. The resulting recommended scantlings are presented in Table 4.5.

Table 4.5: Recommended scantlings

Panel type	t_{plate} [m]	π_{HP}	s_{stiff} [m]	s_{web} [m]
Shell (AW)	**0.007 → 0.009**	HP80×6	**0.35→0.45**	1.50
Shell (BW)	0.008	HP80×6	**0.35→0.50**	1.50
Bottom shell	0.008	HP80×6	**0.35→0.50**	1.50
Weather deck	0.006	HP80×6	**0.475→0.50**	1.50
Inner decks	0.005	HP80×6	**0.475→0.50**	1.50
Tanktop	0.006	HP80×6	**0.475→0.50**	1.50

Cost and mass reduction potential

A direct comparison between the cost reference panels and the strength reference panels demonstrates that a substantial portion of the achievable cost and mass reduction can be realised without advanced optimisation techniques or radical design changes. This confirms that historically conservative design choices leave measurable room for improvement, even within a strictly rule-based design framework.

Because the investigated panel categories represent different structural extents within the hull, a direct arithmetic averaging of panel-level KPI reductions would not accurately reflect system-level impact. Larger structural areas inherently contribute more strongly to total mass, production effort, and complexity than smaller regions.

To provide structural context for the relative importance of each panel type, area-based representation factors are derived from the representative reference panel dimensions defined in Table 4.1. The resulting structural shares, presented in Table 4.6, indicate the proportional geometric contribution of each panel category to the hull.

Table 4.6: Area-based weighting factors derived from reference panel dimensions

Panel type	Total reference area [m^2]	Weight [%]
Bottom shell	600	19.6
Shell (below WL)	300	9.8
Shell (above WL)	360	11.8
Weather deck	400	13.1
Tanktop	600	19.6
Inner decks	800	26.1
Total	**3060**	**100**

These area-based factors are provided for interpretation purposes only and are not used in the KPI aggregation itself. The total reductions reported in Table 4.7 are obtained by aggregating the absolute KPI contributions of each panel type at hull level, rather than by arithmetic averaging of percentage reductions.

Table 4.7: KPI evaluation of recommended scantlings

Panel type	Costs [%]	Part count [%]	Mass [%]	CO_2 [%]	Lead time [%]
Shell (AW)	-24.0	-55.97	9.44	9.06	-29.49
Shell (BW)	-20.5	-27.55	-7.97	-7.97	-23.49
Bottom shell	-20.5	-26.76	-7.65	-7.82	-23.99
Weather deck	-3.29	-4.91	-1.25	-1.25	-3.84
Inner decks	-3.43	-4.96	-1.42	-1.45	-3.93
Tanktop	-3.30	-4.90	-1.24	-1.27	-3.80
Total	**-11.80**	**-17.60**	**-2.40**	**-2.52**	**-13.18**

Across all panel types, the recommended configurations demonstrate consistent reductions in production cost and part count, which directly translate into lower assembly effort and shorter lead times. The primary cost reduction drivers are the bottom and shell panels, due to their relatively large changes in scantling dimensions.

For the deck structures, the reduction potential is lower, as the original *as-is* design already featured relatively large stiffener spacings. In the interest of standardisation, the stiffener spacing of these decks has been increased to match that of the double bottom and shell below the waterline.

Notably, it was initially assumed that increasing scantling dimensions to reduce production cost would inevitably lead to an increase in structural mass. This assumption only holds when the original scantling configuration is already strength- or quality-optimal, which was not the case for the analysed *as-is* design. The present evaluation demonstrates that, for the recommended configurations, all KPIs show an overall positive performance.

While these results indicate consistent improvements across structural, production, and cost-related indicators, they remain inherently subject to modelling assumptions and parameter variability. Given the one-off nature of superyacht construction and the limited availability of statistically validated production data, it is essential to assess not only the magnitude of the improvements, but also their robustness under uncertain input conditions. The following section therefore introduces an explicit uncertainty modelling framework to evaluate the sensitivity and stability of the proposed design recommendations.

4.2.2. Uncertainty modelling, propagation and robustness assessment

To assess whether the observed performance improvements remain valid under realistic variability, uncertainty was explicitly incorporated into the evaluation framework. Rather than focusing solely on nominal KPI values, the robustness of the recommended configurations was analysed by examining their sensitivity to variations in key production and cost drivers.

Uncertainty modelling is particularly necessary in the context of one-off steel superyacht construction. Many input parameters within the framework are derived from expert judgement, historical yard data, and averaged labour coefficients rather than statistically validated, large-sample datasets. Production effort is inherently influenced by worker-specific performance differences, learning effects, sequencing decisions, and project-specific execution conditions. Consequently, the use of deterministic average values may create an impression of precision that does not reflect the variability present in practice.

Due to the limited availability of statistically representative datasets, uncertainty cannot be characterised using classical probability distributions based on large samples. Instead, uncertainty was modelled through expert-informed parameter ranges applied to a limited set of dominant production drivers. This approach deliberately avoids artificial precision while capturing the principal sources of variability that influence early-stage design decisions.

To ensure transparency, the propagation of these input uncertainties through the structural evaluation and Feature-Based Costing calculations was explicitly analysed. By examining how variations in key assumptions influence cost-related KPIs and configuration ranking, the framework avoids reliance on single-point estimates and instead evaluates the stability of design recommendations under plausible variability.

The objective of this analysis is therefore not to predict exact cost spreads, but to determine whether the relative ranking of the recommended configurations remains stable under realistic fluctuations in labour productivity, cost coefficients, and structural parameter assumptions. In this way, the framework supports robust early-stage decision-making rather than deterministic optimisation based on potentially fragile assumptions.

Uncertainty representation

Uncertainty was introduced through multiplicative factors applied to nominal model inputs. These factors represent variability in production efficiency and execution conditions while preserving the deterministic structure of the structural and cost models. For each uncertainty source, a triangular distribution was defined using minimum, nominal, and maximum values. Triangular distributions were selected as they are well suited for expert-based estimation in data-scarce environments.

Three primary uncertainty drivers were considered:

- **Welding speed factor** (f_{ws}), representing variability in effective welding productivity due to accessibility, welding position, operator performance, and working conditions.
- **Assembly time factor** (f_{at}), capturing uncertainty in assembly and handling time arising from congestion, sequencing efficiency, and execution conditions.

- **Part-count (work-content) factor** (f_{pc}), representing variability in detailing level and handling effort associated with part breakdown strategy and local reinforcement complexity.

The adopted uncertainty ranges are summarised in Table 4.8. All factors are centred around unity, such that uncertainty introduces dispersion without structurally biasing results towards improvement or deterioration.

Table 4.8: Uncertainty factors for production parameters

Uncertainty	Min	Nom	Max
Weld speed	0.85	1.00	1.15
Assembly time	0.75	1.00	1.25
Part count	0.90	1.00	1.10

Derivation of labour-hour scaling factors

Since labour hours form the primary driver of cost and lead-time KPIs, sampled uncertainty factors were translated into derived scaling factors for welding and assembly hours, ensuring that physical relationships between work content, productivity, and required effort were preserved.

Welding hours were assumed proportional to work content and inversely proportional to welding speed. For Monte Carlo sample k:

$$f_{\mathrm{WH},k} = \frac{f_{pc,k}}{f_{ws,k}}. \tag{4.2.1}$$

Assembly hours were assumed proportional to both work content and assembly-time variability:

$$f_{\mathrm{AH},k} = f_{pc,k}\, f_{at,k}. \tag{4.2.2}$$

Nominal labour hours were then scaled as:

$$H_{\mathrm{weld},k} = H_{\mathrm{weld,nom}}\, f_{\mathrm{WH},k}, \qquad H_{\mathrm{ass},k} = H_{\mathrm{ass,nom}}\, f_{\mathrm{AH},k}. \tag{4.2.3}$$

These scaled labour-hour values constitute the primary stochastic inputs for KPI evaluation.

Monte Carlo uncertainty propagation

Uncertainty propagation was performed using a Monte Carlo simulation approach. A total of $N = 3000$ random samples were drawn from the defined triangular distributions. For each sample, the derived welding and assembly hours were propagated through the deterministic KPI model to compute cost, lead time, mass-related, and environmental indicators.

Material-related KPIs were derived from structural mass and were therefore influenced only indirectly by uncertainty when mass itself varied. Transport costs were treated as proportional to mass and followed the same uncertainty propagation mechanism.

To ensure a fair comparison between the reference and selected configurations, identical Monte Carlo samples were applied to both designs. This implies that both alternatives were evaluated under identical sampled production conditions. As a result, uncertainty components common to both configurations partially cancel out when computing relative performance metrics. This approach reflects the practical reality that alternative designs would be produced within the same shipyard environment and prevents artificial inflation of uncertainty in the estimated reductions.

Result extraction and robustness assessment

For each KPI, the Monte Carlo simulation produced a distribution of outcomes. Uncertainty bounds were quantified using the 10th, 50th, and 90th percentiles (P10, P50, and P90). Relative improvements between the reference and selected configurations were computed on a per-sample basis prior to extracting percentile statistics, thereby preserving correlations between KPIs and uncertainty drivers.

The resulting uncertainty bounds on total KPI reductions are summarised in Table 4.9. Even under conservative assumptions (P10), the selected configuration consistently delivers meaningful reductions in production cost, lead time, and part count.

Table 4.9: Total KPI reduction with uncertainty bounds (P10–P50–P90)

KPI	P10	P50	P90
Part count	16.57%	17.60%	18.58%
Mass	2.20%	2.34%	2.47%
CO_2	2.31%	2.46%	2.59%
Lead time	11.09%	12.48%	13.79%
Costs	9.70%	10.81%	11.86%

Table 4.10: Normalised uncertainty factors derived from Monte Carlo simulation (P50 = 1.0)

KPI	P10	$P50_{norm}$	P90
Part count	0.94	1.00	1.06
Mass	0.94	1.00	1.06
CO_2	0.94	1.00	1.06
Lead time	0.89	1.00	1.11
Costs	0.89	1.00	1.10

The relatively narrow uncertainty bands associated with mass- and CO_2-related KPIs reflect their predominantly geometry-driven nature. In contrast, the wider uncertainty ranges observed for cost and lead time are primarily attributable to execution-related variability inherent to one-off superyacht production.

Due to confidentiality constraints, results are reported primarily in relative terms in the main body of this thesis. Absolute KPI values and panel-level results are provided in Appendix **??**.

4.2.3. Concluding remarks

The analyses presented in this section demonstrate that the primary research objective of achieving a 10–15% reduction in steel hull production cost can be realised through conservative and immediately implementable adjustments of structural scantlings. By selecting configurations that remain fully compliant with classification rules and closely aligned with established shipyard practice, the proposed recommendations avoid the risks typically associated with radical design changes or advanced optimisation strategies.

The deterministic KPI evaluation, complemented by the stochastic robustness assessment presented in Section 4.2.2, confirms that the observed improvements are structurally admissible and remain stable under realistic production variability. The recommended configurations therefore provide a practical and low-risk pathway to achieve targeted cost reductions within a rule-consistent design framework.

These results establish a credible and immediately applicable baseline for short-term implementation, while simultaneously offering a structured foundation for further optimisation and standardisation in subsequent design phases.

Beyond the interpretation of the obtained design recommendations, it is necessary to assess the behaviour and reliability of the underlying methodological framework itself. While the previous section demonstrated that the proposed scantling adjustments achieve the targeted cost reductions under the defined assumptions, the robustness and internal coherence of the modelling approach must also be evaluated explicitly. The following section therefore examines the validity of the proposed framework against the predefined validation criteria.

4.3. Validation of the proposed framework

This section evaluates the behaviour of the proposed framework against the validation criteria defined in Section 3.3.7. Validation focuses on internal consistency, plausibility of model behaviour, and the framework's ability to support comparative decision-making. The assessment is based on the observed outcomes of the structural optimisation, Feature-Based Costing (FBC) evaluation, and KPI analysis applied to the selected panel configurations.

Structural admissibility under rule-consistent constraints All evaluated design variants are assessed using a consistent structural screening approach that combines classical stiffened plate theory with Lloyd's Register rule-based pressure formulations. This approach is intentionally applied as an early-stage approximation to ensure comparability between design alternatives, rather than as a substitute for full class-compliant structural verification.

Design configurations that violate stress, buckling, or deflection limits within this modelling framework are systematically excluded from further evaluation. All reported results are therefore generated under a uniform set of Lloyd's-consistent structural constraints and yard-specific production limitations. When existing ("as-is") stiffener spacing configurations are evaluated, the optimisation framework explicitly reconstructs the corresponding reference panel configuration. This ensures that comparisons between existing and alternative designs are made on an equivalent structural and modelling basis.

As a result, all KPI comparisons are restricted to structurally admissible configurations within the applied assumptions, ensuring that observed differences in production-related performance are not driven by structurally unrealistic solutions. At the same time, it is acknowledged that final verification would require more detailed, class-compliant analysis.

Internal consistency of model behaviour Systematic variation of key structural design parameters, such as stiffener spacing and plate thickness, results in consistent and physically interpretable trends across production-related KPIs. Increasing stiffener spacing leads to reduced part count and weld length, while increased plate thickness primarily affects material-related cost contributions. These monotonic trends are observed consistently across all evaluated panel types, indicating coherent internal model behaviour.

Validation of the cost model is therefore performed through assessment of internal cost distributions rather than absolute cost levels. In the absence of project-specific production data, the relative contribution of material, metal work, and welding effort provides a robust indicator of model plausibility.

Historical Feadship production records indicate that material costs typically account for approximately 15% of total production costs, with the remaining share dominated by labour-intensive activities. Within this labour component, a typical ratio of approximately 60% metal work to 40% welding effort is observed. These reference values include both hull construction and outfitting activities.

The results presented in Table 4.3 show material cost shares ranging from approximately 18% to 26%. The relatively higher material fraction is consistent with expectations, as the analysed scope focuses on comparatively simple structural panels and excludes a substantial portion of outfitting-related labour included in the historical reference values. Across most configurations, the ratio between metal work and welding remains stable, with welding representing approximately 62–71% of metal work effort, aligning well with yard-observed production characteristics.

A notable deviation is observed for the Above Waterline reduced configuration, where the welding-to-metal-work ratio increases significantly. This deviation is directly attributable to the removal of buckling plates, which reduces fabrication effort while maintaining a relatively high welding demand. The resulting shift in cost structure is therefore explainable based on structural characteristics and does not indicate an artefact of the modelling approach.

Differentiation between design alternatives The framework consistently differentiates between structurally feasible design alternatives by producing distinct KPI profiles. Design variants that are structurally comparable exhibit measurable differences in production cost, lead time, and complexity-related indicators. This demonstrates that the framework provides sufficient resolution to distinguish between competing design strategies, rather than converging towards a single undifferentiated solution.

Trade-off visibility The results show that improvements in production cost are accompanied by consequences for secondary performance indicators. Configurations with lower production cost tend to exhibit increased structural mass, CO2 emissions, or gross tonnage, depending on the applied design measures. No single configuration outperforms all others across all KPIs, confirming that the framework exposes explicit trade-offs rather than implicitly enforcing a single optimum.

Behaviour of lead-time estimates Lead-time estimates respond consistently to dominant production complexity drivers. Variants characterised by reduced part count and lower welding effort exhibit systematically lower lead-time values. This behaviour aligns with established production knowledge and supports the use of lead time as a meaningful comparative KPI within the proposed framework.

Robustness of relative results Sensitivity analyses indicate that the qualitative ranking of design alternatives and dominant KPI trends remain stable under reasonable variation of modelling assumptions. While absolute KPI values vary as expected, the relative comparison between design options is preserved. This indicates that the main conclusions are robust and not driven by isolated parameter choices.

In summary, the observed results demonstrate that the proposed framework behaves coherently, produces interpretable and plausible outcomes, and supports explicit trade-off analysis between structurally admissible design alternatives within a Lloyd’s-consistent early-stage modelling context. Validation is therefore achieved in terms of comparative decision-support capability rather than absolute cost prediction accuracy.

The results presented in this chapter demonstrate that production-oriented adjustments of structural scantlings can yield measurable cost reductions while maintaining rule compliance and structural robustness. The combined deterministic, stochastic, and validation analyses confirm both the technical feasibility and the internal consistency of the proposed framework within the defined project scope.

However, the interpretation of these findings extends beyond the numerical results themselves. The assumptions underlying the modelling approach, the limitations inherent to one-off superyacht production, and the broader implications for Design for Production practice require further reflection.

The following chapter therefore discusses the theoretical, methodological, and practical implications of the study, positioning the results within the wider context of shipbuilding optimisation and production-oriented design.

5

Discussion

This chapter interprets and contextualises the results of the research by linking the qualitative and quantitative findings to the broader objectives of Design for Production in one-off superyacht construction. Rather than restating individual results, the discussion focuses on explaining observed trends, addressing non-intuitive outcomes, and reflecting on their implications for early-stage structural design decision-making.

The chapter first examines how expert-based prioritisation of Design for Production guidelines compares to quantitatively observed production effects. It then discusses the added value of coupling structural optimisation with Feature-Based Costing–based KPI evaluation, before synthesising qualitative and quantitative insights. Finally, the discussion reflects on the limitations, risks, and opportunities associated with the adopted methodology, providing context for interpretation and outlining directions for future research and industrial application.

5.1. Interpretation of DfP guideline prioritisation, IAR results

The IAR results demonstrate a clear preference for process oriented Design for Production, DfP, guidelines over design oriented structural interventions. This prioritisation reflects expert judgement rather than measured production impact. While design oriented measures that directly affect structural scantlings receive lower priority scores, the subsequent quantitative analysis indicates that their potential cost impact can be substantial.

When reviewing the IAR scores independently, the estimated reduction potential of implementing larger frame spacing combined with thicker plating was approximately 9.2%, which aligns closely with the reduction identified in the quantitative assessment. Despite this, the Applicability and Importance criteria received comparatively lower scores. In contrast, the quantification results reveal that part count reduction can be significant, an objective that according to existing literature represents a central goal of DfP.

The observed prioritisation may be influenced by context specific factors related to organisational practices and project characteristics. Previous studies suggest that part count reduction is typically regarded as a primary objective in DfP strategies. However, risk perception in highly customised, one off superyacht construction environments may differ substantially from that in serial production contexts. These findings indicate that expert based prioritisation should be interpreted primarily as an assessment of perceived implementability rather than objective effectiveness, reinforcing the importance of complementing qualitative expert judgement with quantitative evaluation to obtain a more balanced and evidence based prioritisation.

5.2. Coupling of optimisation and FBC-based KPI evaluation

The coupling of structural optimisation and Feature-Based Costing (FBC)-based Key Performance Indicator (KPI) evaluation represents a central insight of this research. Rather than treating optimisation outcomes as definitive solutions, the results demonstrate that optimisation gains meaning primarily when interpreted within a broader production-oriented performance context. This finding reinforces the notion that early-stage structural design decisions cannot be evaluated on cost considerations alone, but must be understood through their interaction with multiple, often competing, production-related objectives.

Optimisation, when applied in isolation, inherently reflects a narrow perspective by focusing on a single objective function. While this enables identification of cost-efficient configurations, it does not capture how structural variations affect other critical aspects of production performance, such as part count, production lead time, or process robustness. As a consequence, cost-optimal solutions do not necessarily align with configurations that are preferable from a holistic production or organisational perspective. This highlights a fundamental limitation of single-objective optimisation in the context of one-off superyacht construction, where design decisions must balance technical feasibility, production effort, and strategic project considerations.

The FBC-based KPI evaluation complements this limitation by providing a multi-dimensional perspective on production performance. By explicitly relating structural design choices to a set of production-oriented KPIs, the framework enables trade-offs between cost efficiency, buildability, and broader process-related implications to be made visible. Importantly, this evaluation does not seek to replace optimisation, but to contextualise it. The optimisation step generates structurally feasible and competitive design alternatives, while the KPI evaluation reveals their broader consequences for production execution and decision-making.

The results further indicate that production-oriented performance is governed by a limited number of dominant drivers, most notably part count. This observation suggests that the impact of early-stage structural decisions emerges primarily through their cumulative effect on production complexity and labour intensity. Such interaction effects are not readily apparent when design variables are assessed independently, underscoring the importance of evaluating optimisation outcomes within a multi-criteria framework.

Taken together, these findings confirm that the primary value of coupling optimisation with FBC-based KPI evaluation lies in decision support rather than optimisation itself. By creating a large set of scantling options to compare, the combined approach enables designers to explore structurally admissible design spaces, understand the trade-offs inherent in alternative configurations, and select balanced solutions that align with project-specific priorities and risk tolerance. In the context of highly customised, one-off superyacht construction, this coupling provides a pragmatic means of translating early-stage structural design freedom into informed, production-aware decision-making.

5.3. Synthesis of qualitative and quantitative findings

The qualitative and quantitative phases of this research address complementary but fundamentally different aspects of production-oriented design decision-making. The IAR results reflect expert perception, organisational priorities, and implementation readiness, whereas the optimisation and FBC-based KPI evaluation provide objective insight into the measurable effects of selected design interventions. The synthesis of these perspectives reveals how expert judgement and analytical evaluation interact, and where they may diverge.

The qualitative IAR phase did not directly determine the quantitative design space, but instead shaped its framing. Rather than selecting individual guidelines for direct implementation, the IAR results informed the selection of a limited set of underlying design principles, most notably design simplification and part count reduction, which were subsequently evaluated quantitatively. This indirect coupling proved essential, as it allowed qualitative insights to guide the analysis without constraining it to expert-ranked solutions alone.

The quantitative results demonstrate that several design-oriented measures, which received relatively low priority in the qualitative ranking, can nonetheless yield substantial production benefits when evaluated in combination. In particular, configurations characterised by increased plate thickness and reduced secondary stiffening illustrate that higher individual scantling values do not necessarily translate into a proportional increase in structural mass. When applied in a balanced manner, the accompanying reduction in part count and structural complexity can even result in a net reduction in structural mass, while simultaneously exerting a dominant influence on production cost, lead time, and process robustness.

At the same time, this synthesis underscores the necessity of explicit trade-off management. While certain configurations are favourable from a production cost and buildability perspective, they may adversely affect other performance indicators such as structural mass, CO_2 emissions, or gross tonnage. These competing objectives necessitate clearly defined feasibility boundaries within which production-oriented improvements can be pursued without compromising product quality, regulatory margins, or brand-related constraints.

This interaction highlights a key limitation of relying solely on qualitative guideline prioritisation for product-oriented Design for Production decisions. Individual guideline rankings do not capture interaction effects between structural measures, nor do they adequately reflect system-level impacts on assembly effort and production flow. Quantitative evaluation is therefore required to reveal such non-intuitive effects and to assess the true production-oriented consequences of structural design changes.

While the synthesis of qualitative and quantitative findings provides valuable insight into the interaction between expert judgement and analytical evaluation, the interpretation and practical application of these results remain subject to a number of limitations and risks. These arise from modelling assumptions, data availability, and execution-related variability, as well as from organisational and contextual factors inherent to one-off superyacht production. To support informed and responsible decision-making, these limitations and associated implementation risks are explicitly addressed in the following section.

5.4. Limitations, Risks and Opportunities

This section reflects on the methodological choices made in this study by discussing their associated limitations, potential risks, and opportunities for further development. The discussion is structured to highlight how specific modelling decisions influence result interpretation and how they simultaneously point towards clear directions for future research and industrial application.

Expert judgement and qualitative prioritisation The prioritisation of Design for Production guidelines in this study relies on expert judgement through the Importance–Applicability–Readiness (IAR) framework. This approach enables the incorporation of tacit knowledge and experience that is difficult to capture through purely quantitative methods, while simultaneously introducing an inherent degree of subjectivity, as expert assessments may be influenced by disciplinary background, organisational context, or individual risk perception. This subjectivity creates a potential risk of bias in the prioritisation outcome, particularly when qualitative preferences are not aligned with measurable production effects. However, this limitation also highlights a key opportunity: combining expert-based prioritisation with subsequent quantitative evaluation allows qualitative intuition to be tested, challenged, and refined. Future research could further strengthen this approach by expanding the expert pool, applying structured consensus-building techniques, or combining expert judgement with data-driven weighting methods.

Structural modelling abstraction and class-related constraints The structural assessment in this study is based on simplified stiffened plate models and standard plate theory, combined with selected Lloyd's Register rule-based loading and strength criteria. This abstraction enables transparent, consistent, and computationally efficient comparison of a large number of design variants at an early design stage, while local geometric details such as brackets, scallops, extreme curvature, window frames, and other aesthetic features are not explicitly modelled. As a consequence, the results should be interpreted as indicative trends rather than class-approved or detailed design solutions. There is a risk that the abstraction level limits the accuracy of absolute structural response predictions when extrapolated beyond early-stage application. At the same time, this modelling choice creates clear opportunities for future development, as higher-fidelity structural models or class-compliant scantling calculations could be integrated in later design stages to refine promising configurations identified by the present framework, while preserving its comparative strengths.

Production effort modelling and data fidelity Production effort is estimated using a Feature-Based Costing framework with a relatively coarse representation of welding and assembly processes. While this level of resolution is sufficient to capture dominant labour drivers such as part count and weld length, it does not explicitly account for workshop specific factors including welding sequence, accessibility constraints, positional welding, or shop floor variability. The use of historical, record based production data further implies that the results reflect generalised production behaviour rather than project specific execution conditions, introducing uncertainty in the absolute magnitude of predicted cost and lead time reductions.

Nevertheless, these modelling choices support robust relative comparison between design variants, which is the primary objective of the framework. Future work could improve model fidelity through project specific calibration, refined process modelling, and explicit representation of execution related variability. The work of Priyanda et al. [27] and Caprace [7] presents DfP process mapping of rework effort through Lean theory, and Neural Networks and Fuzzy Logic respectively, which could be applied to address such complex nonlinear relationships in future research.

Scope limitations and system-level interactions The present analysis focuses on panel-level structural elements and does not fully integrate global hull behaviour or system-level interactions. Effects such as global stiffness redistribution, stability, gross tonnage, and interactions between structure and outfitting elements therefore fall outside the scope of this study. This limitation introduces a risk that panel-level optimisation results are interpreted as globally optimal solutions. However, the panel-level focus is a deliberate choice aligned with early-stage design decision-making, where local structural choices dominate production effort. The framework can be extended in future research by coupling panel-level optimisation with global structural and naval architectural models, enabling more holistic assessment without compromising early-stage applicability.

Interpretation, uncertainty and decision-making context Although uncertainty modelling and stochastic robustness assessment have been explicitly incorporated in this research, the framework remains based on simplified structural abstractions and expert-informed parameter ranges rather than statistically validated production datasets. As a result, the quantitative outputs should not be interpreted as precise cost predictions, but as structured approximations of relative design performance within a bounded feasibility space.

The inclusion of uncertainty propagation mitigates the risk of false precision by explicitly capturing variability in dominant production drivers. Nevertheless, model outcomes remain sensitive to the selected parameter ranges and calibration assumptions. Engineering judgement therefore remains essential when interpreting absolute KPI values and recommended configurations.

Accordingly, the proposed framework should be understood as a decision-support tool rather than a deterministic optimisation engine. Its primary strength lies in revealing relative trends, dominant cost drivers, and robust design directions under realistic variability, rather than in predicting exact production costs.

Future refinement could focus on expanding empirical calibration datasets, integrating yard feedback from implemented configurations, and developing probabilistic visualisation methods that further enhance transparency of model assumptions and result robustness.

The discussion has shown that the effectiveness of Design for Production measures in one-off superyacht hull construction cannot be understood through qualitative judgement or quantitative optimisation in isolation. Instead, meaningful production-oriented design decisions emerge from the interaction between expert perception, analytical evaluation, and explicit trade-off management within clearly defined feasibility boundaries. By interpreting expert-based guideline prioritisation alongside optimisation and Feature-Based Costing–based KPI evaluation, this chapter has demonstrated how design-oriented interventions can yield substantial production benefits despite being perceived as higher risk. At the same time, the discussion highlights the importance of careful interpretation, engineering judgement, and organisational context when applying such measures in practice. Building on these insights, the following chapter consolidates the main contributions of this research and formulates overall conclusions, reflecting on how the proposed framework addresses the identified research questions, discussing its relevance for industrial application, and outlining recommendations for future research and implementation in the context of bespoke superyacht construction.

6

Conclusion

This thesis investigated how Design for Production principles can be operationalised to achieve cost reductions in one-off steel superyacht hull construction, without compromising structural integrity, classification compliance, or production robustness.

By combining a structured literature review, expert-based guideline prioritisation, rule-informed structural generation, Feature-Based Costing evaluation, and uncertainty analysis, a decision-support framework was developed and applied to representative hull panels. The results demonstrate that conservative adjustments to structural scantlings can yield measurable cost savings within realistic shipyard constraints.

This chapter synthesises the key findings of the research and with that explicitly answers the research questions and main research question. It then reflects on the academic and practical contributions of the study and outlines recommendations for future research.

6.1. Key Findings

This chapter synthesises the principal findings of the research by distilling the results from the literature review, expert-based guideline prioritisation, structural optimisation and production-oriented KPI evaluation into five key findings. Together, these findings summarise how Design for Production principles can be operationalised to support early-stage structural decision-making for cost reduction in highly customised, one-off superyacht hull construction, while respecting structural integrity and quality-related constraints.

Design for Production knowledge is abundant but fragmented The literature review demonstrates that a substantial body of Design for Production–oriented knowledge exists within shipbuilding research and practice. Across academic and industry sources, a wide range of Design for X guidelines addressing producibility, assembly effort and manufacturing complexity can be identified. However, this knowledge is fragmented across different contexts and levels of abstraction, and is rarely consolidated into a framework that is directly applicable to highly customised, one-off superyacht hull construction.

As a result, existing Design for Production guidance remains difficult to apply directly in early-stage superyacht design, where structural decisions must be made under uncertainty and strong aesthetic constraints. This fragmentation necessitates structured synthesis and context-specific filtering before such knowledge can be operationalised in practice.

The relevance of Design for Production guidelines is highly context-dependent The expert-based prioritisation reveals a clear preference for process-oriented Design for Production guidelines over design-oriented structural interventions. Measures related to coordination, feedback loops and production planning are consistently prioritised due to their perceived low implementation risk and limited impact on structural geometry and scantlings.

However, this prioritisation reflects expert risk perception rather than quantitative impact. While design-oriented measures receive lower qualitative scores, the subsequent quantitative analysis demonstrates that their potential influence on production cost is substantially greater than anticipated. This finding highlights an inherent tension between expert intuition and measurable production outcomes, underscoring the need to complement qualitative prioritisation with quantitative evaluation.

Qualitative Design for Production principles can be translated into quantitative structural design variables The study demonstrates that qualitative Design for Production principles can be translated into quantitative early-stage analysis by abstracting them into a limited set of structural design parameters. Rather than implementing individual guidelines directly, the underlying intent of reducing structural complexity and part count provides a robust basis for quantitative evaluation.

By expressing these principles through variations in parameters such as stiffener spacing, plate thickness and secondary stiffening density, a controlled design space can be generated that captures dominant production effects. Within this framework, structural simplification does not necessarily lead to an increase in total structural mass, but instead enables mass redistribution within the structure. This allows cost-reducing design measures to be explored while maintaining structural integrity and quality-related constraints.

Production cost reduction is governed by a small number of dominant key performance indicators The quantitative results show that production cost reduction through structural complexity reduction is primarily governed by a small number of dominant production-oriented key performance indicators. Among these, part count emerges as the most influential driver, as it directly affects welding effort, assembly time, labour intensity and production lead time.

Other indicators, including material cost, structural mass and sustainability-related metrics, act primarily as governing constraints rather than optimisation objectives. These factors define the feasible design space within which production-oriented optimisation can take place, reinforcing the importance of explicitly linking early-stage structural design choices to labour-driven KPIs.

Validated early-stage production cost reduction potential within structural constraints The results indicate that meaningful production cost reductions can be achieved when design-oriented Design for Production measures are applied in a coherent and production-focused manner. Cost reductions on the order of 10–15% are observed within the evaluated cases, subject to structural and performance constraints.

However, the primary contribution of the proposed framework lies not in identifying a single optimal solution, but in enabling informed early-stage decision-making. Structural optimisation and Feature-Based Costing–based KPI evaluation are shown to be mutually dependent: optimisation ensures structural feasibility and comparability, while KPI evaluation captures broader production and process-related impacts. Together, they provide a transparent basis for selecting balanced design solutions aligned with project-specific priorities and risk tolerance.

6.2. Answer to the Main Research Question

The main research question was formulated as follows:

> **MRQ:***"How can established Design for Production principles in shipbuilding be applied to reduce production cost in highly customised, one-off superyacht construction through early-stage structural design complexity reduction, while maintaining structural integrity and quality?"*

This research demonstrates that established Design for Production (DfP) principles can be effectively applied to highly customised, one-off superyacht construction when they are operationalised through early-stage structural design parameters and evaluated within a production-oriented decision-support framework. Rather than applying individual DfP guidelines as isolated rules, their value emerges when qualitative producibility principles are translated into quantitative design variables that directly influence production effort.

The findings show that early-stage structural design decisions primarily affect production cost through a limited set of dominant drivers, most notably part count and associated assembly and welding effort. By reducing structural complexity through coordinated adjustments of structural scantlings, meaningful production cost reductions on the order of 10–15% can be achieved within a rule-consistent and quality-controlled design space.

Structural integrity and quality are maintained by constraining all evaluated design alternatives within a structurally admissible framework, ensuring that cost reductions are realised without compromising safety or established design standards. Within these boundaries, the application of DfP principles does not lead to a single optimal solution, but supports informed trade-offs between cost-driving performance indicators and governing constraints.

Accordingly, the application of Design for Production principles functions primarily as a decision-support mechanism. By enabling designers to explore structurally feasible design spaces and evaluate the production implications of alternative configurations, the proposed framework supports balanced early-stage design decisions that achieve cost reduction while respecting project-specific priorities, structural integrity, and quality requirements.

6.3. Contributions

This thesis contributes to both academic research and engineering practice in the field of production-oriented ship design, with specific focus on highly customised, one-off superyacht construction.

First, a novel decision-support framework is developed that integrates Design for Production principles, early-stage structural evaluation, and production-oriented Key Performance Indicators. While these elements exist individually in literature, their combined application to early-stage structural design in bespoke superyacht hull construction has not previously been addressed in an integrated manner.

Second, the research provides an operationalisation of qualitative Design for Production guidelines into concrete, quantifiable early-stage structural design parameters. By linking principles such as structural simplification and part count reduction to parameters such as stiffener spacing, plate thickness, and weld length, the study enables quantitative evaluation of producibility-oriented design choices that are traditionally addressed qualitatively.

Third, the framework is applied in the specific context of one-off superyacht hull construction, demonstrating how established shipbuilding methods can be adapted to a highly customised, aesthetics-driven production environment, by introducing industry specific feasibility spaces. This contextual application highlights both the limitations of existing methods and the adjustments required to make them applicable in bespoke production settings.

Fourth, the research validates the qualitative statements of part count being the dominant production-oriented cost drivers in early-stage structural design. The results show that a limited set of Key Performance Indicators, particularly part count, govern production cost and lead time, while other indicators primarily act as governing constraints. This insight supports more focused and effective design decision-making.

Finally, the study delivers practically applicable insights by presenting representative, panel-type-specific structural configurations that illustrate how Design for Production principles can be applied within structurally admissible and quality-consistent boundaries. These recommendations demonstrate the practical value of the proposed framework while preserving its role as a decision-support tool rather than an optimisation prescription.

6.4. Directions for further research

Several directions for further research follow logically from the scope and limitations of this study.

First, future work is recommended to quantitatively assess process-oriented Design for Production measures. While such measures are consistently prioritised by experts due to their perceived low risk and high implementability, their actual impact on production cost, lead time, and process robustness remains insufficiently quantified. Process modelling and discrete-time simulation approaches, as demonstrated in ship production planning research [24], could be integrated to explicitly capture production flow interactions and execution-related dynamics.

Second, the proposed framework could be extended towards multi-objective and multi-level analysis by incorporating global vessel performance indicators and full hull integration. Multi-objective optimisation approaches based on Pareto frontier analysis have been successfully applied to ship design decision-making problems [36]. Integrating similar methodologies would enable systematic evaluation of interactions between local structural optimisation and overall vessel behaviour, thereby supporting more holistic design decision-making.

Third, application of the framework to fully defined, project-specific superyacht cases would allow validation of predicted trends against realised production data. Case-based implementation studies have demonstrated the value of applying feature-based costing approaches in complex vessel projects [7]. Such validation would improve confidence in the industrial applicability of the proposed framework and clarify project-dependent boundary conditions.

Finally, further research could explicitly address execution-related variability and organisational decision dynamics. Probabilistic modelling of production effort and integration of organisational readiness or implementation constraints would enhance the robustness and realism of early-stage decision support in bespoke shipbuilding environments. Extending the framework towards uncertainty-aware and robustness-oriented analysis would further strengthen its applicability in practice.

Closing Remarks

This thesis has demonstrated that Design for Production principles can be systematically embedded in early-stage structural decision-making for bespoke superyacht construction. By integrating structural feasibility, production-oriented evaluation, and uncertainty awareness within a coherent framework, the research provides a structured basis for aligning design choices with production performance in highly customised environments.

Although further refinement and industrial validation remain necessary, the presented approach establishes a transparent and extensible foundation for production-driven structural optimisation in one-off shipbuilding practice.

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