Application of Model Based System Engineering (MBSE) with Ship Design Arrangement Tool of advanced zero emissions Power, Propulsion and Energy Systems in Maritime Technology.

MSc Thesis Report MT.21/22.045.M

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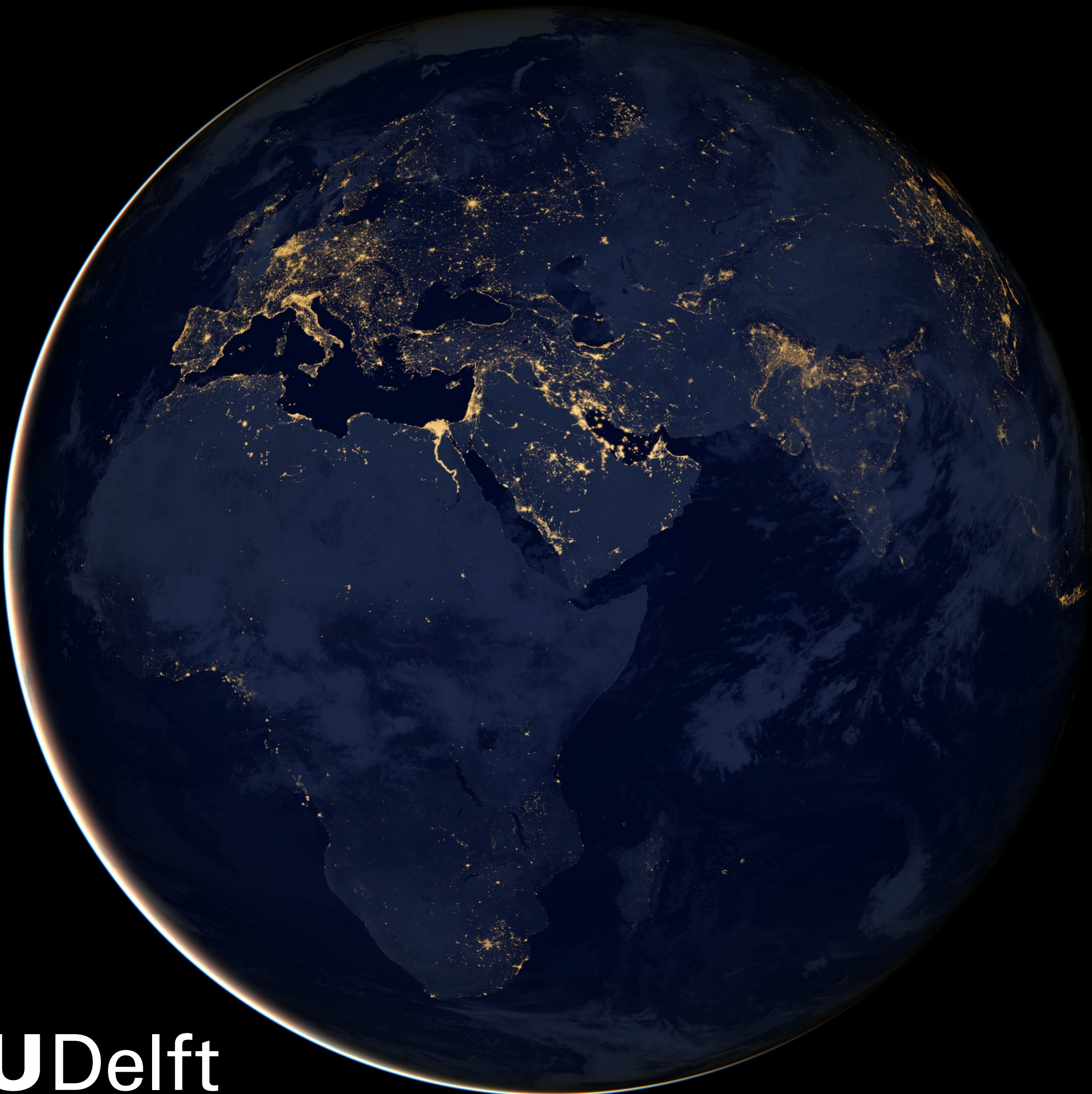

Delft University of Technology

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by

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MARIN

BETTER SHIPS, BLUE OCEANS

TU Delft

Preface

The main aim of the master thesis was to create a design tool for the arrangement of the Propulsion, Power and Energy (PPE) systems during the conceptual design stage in cooperation with Maritime Research Institute of Netherlands (MARIN). MARIN initiated the ZERO Joint Industry Project (JIP) where several leading maritime sector companies and organisations participate to prepare for the maritime industry's transition towards sustainability. Within ZERO JIP, a recent and novel methodology known as Model Based Systems Engineering (MBSE) is implemented to aid in the design process of either fully or partly Zero Emission Ships (ZESs). The arrangement design tool developed in this master thesis needed to provide initial PPE layouts in the conceptual design stage and work as an add-on to the MBSE methodology and the Ship Power and Energy Concept (SPEC) tool, an in-house tool developed by MARIN. Currently, the MBSE methodology and the SPEC tool cannot directly generate the spatial arrangement guidance needed for the actual PPE system layouts. The design tool developed is the final necessary step needed between the important physical design details captured within the MBSE and the SPEC tool and the generation of arrangement layouts across a 2-dimensional physical space. In other words, the design tool developed uses the MBSE methodology and SPEC tool details as inputs for the generation of PPE system layouts during the conceptual design stage.

MBSE is a relatively new and innovative methodology with very limited application in ship design. It was essential within the current report to provide an extensive literature to make the reader familiar with the MBSE methodology and its origin. It was an additional thesis aim to elaborate why the MBSE methodology has been decided to be implemented within MARIN and what it can offer. Therefore, at the start of the report the current maritime emission trends together with the sector's future targets are identified. The increased complexity and multifaceted challenges from the early design stages of ZESs are elucidated and the criticality of the conceptual stage are established. Additionally, a detailed overview of the different design techniques currently available in the maritime sector are provided, uncovering their benefits and limitations. Next, the MBSE methodology and its benefits are introduced and how it can aid with the ZESs design challenges. The MBSE Arcadia methodology used at MARIN is presented. The application of the MBSE methodology and its current role in ship design is discussed.

An overview on how the MBSE methodology is currently implemented within the ZERO JIP of ZESs is provided within this report. Additionally, the Ship Power and Energy Concepts (SPEC) tool developed by MARIN to enable the exploration of different Power and Propulsion Energy (PPE) systems is explored. This is an innovative design tool that enables the extensive comparison between different PPE systems based on multi-criteria analysis. After elaborating on the importance of the MBSE methodology implementation and the design procedure followed within MARIN using MBSE methodology and SPEC tool, the identified gap within both the literature and MARIN design process is explained. This provided a clear understanding on the method requirements and objectives the PPE system design arrangement tool needs to achieve. It is important to state from the start that this MSc thesis is not a part of the ZERO Joint Industry Project, but is supported by using MARIN's SPEC tool, MBSE architectures and a JIP's specific Use Case.

The selected modelling and resolution approach for developing the design tool is elaborated, after observing the different possible solution directions found on literature. Following that, the developed PPE system design tool's methodology is explained in detail. The design tool is tested on a specific use case, a large motor yacht and various observations are discussed for the generation of these layouts. Furthermore, the design tool's generated layouts is compared using a baseline layout and the influence of input uncertainties is tested. Finally, before validating the design methodology of the developed tool and providing the thesis conclusions and future recommendations, the tool's limitations are elaborated.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
CAD	Computer-aided design
CAPEX	Capital expenditure
CCS	Carbon Capture and Storage
CD	Concurrent Design
CFD	Computational Fluid Dynamics
C&RE	Concept and Requirements Exploration
DF	Dual Fuel
DRM	Design Reference Mission
DMO	Defence Materiel Organisation
DWT	Deadweight
ECA	Emission Control Area
EMS	Energy Management System
EPDT	Event power distribution table
EPTC	Event power time chart
FEM	Finite Element Methods
GAP	General Arrangement Plan
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
HLCV	Heavy Lift Crane Vessel
HPS	Hybrid Propulsion System
ICE	Internal Combustion Engine
IMO	International Maritime Organization
INCOSE	International Council on Systems Engineering
JIP	Joint Industry Project
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MBSE	Model Based Systems Engineering
MPTC	Mission Power Time Chart
OPEX	Operating Expenses
PPE	Power and Propulsion Energy
PTC	Power Time Characteristics
PTI	Power Take In
PTO	Power Take On
SBD	Set Based Design
SE	Systems Engineering
SPEC	Ship Power and Energy Concept
TTW	Tank to Wake
TCO	Total Cost of Ownership
UNCTAD	United Nations Conference on Trade and Development
WTT	Well to Tank
WHRS	Waste Heat Recovery System
ZE	Zero Emission
ZES	Zero Emission Ship

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Decarbonization in the Maritime Industry

1.1. Future Emission Targets & Current Trends

Global emissions have soared by two-thirds since the beginning of the international climate talks three decades ago, with decarbonization becoming a global imperative [1]. A string of continuous efforts and technological revolutions is required to address this enormous challenge, especially in harder-to-abate sectors that vastly contribute to the global emission footprints such as the maritime sector. A great paragon of this sector category is shipping and together with the industry's extended asset lifespans and the high energy dependency, immediate technological progress is essential.

The International Maritime Organization (IMO) set a target at reducing the carbon intensity from international shipping (CO_2 emissions per transport work) by at least 40% by 2030 and 70% by 2050 and the total annual greenhouse gas (GHG) emissions by at least 50% by 2050 compared to 2008 [2]. Even more challenging, the EU specifically aims at a 70% GHG emission reduction. All these regulations are addressing international shipping only. Other regional regulations concerning smaller shipping vessels are equally important, such as the European Stage V that includes stricter emission standards for inland ships [3]. Additionally, in Emission Control Areas (ECAs) consisting of the Baltic, the North Sea, the North American Sea and the United States Caribbean Sea tighter emission caps are in place. A tougher sulphur emission cap of 0.1% is already in place for the ECAs compared to the 0.5% that came in force after for international waters in 2020 [4]. By January 2020, the world fleet tonnage has increased to a total carrying capacity of 2.1 billion DWT [5]. These emission reductions refer to the fleet level and the current existing vast seagoing tonnage is predominantly not efficient. Recent analytical results from the IMO, Classification Societies and the International Energy Agency (IEA), revealed the total fuels used in the worldwide fleet corresponding to low or zero carbon-content alternative fuels is less than 2% [6], [7], [8]. Thus, intense efforts for the emergence of low carbon, novel ships are required. New-build ships need to be able to achieve zero emission performances in order to achieve the fleet level reductions.

Shipping is considered to be the backbone of the global economy and responsible for around 2.7% of global emissions and as the industry continually develops, emissions further continue to increase [9]. According to the United Nations Conference on Trade and Development (UNCTAD) statistics, it accounts for about 80% of the total volume traded around the globe. From 2000 until 2018, volumes transported by shipping increased by 93% [10]. This rapid increase in shipping volumes, raises the pressure to accelerate zero emission shipping. The major emissions generated in shipping consist of CO_2, nitrogen oxides (NO_x), sulphur oxides (SO_x), and particular matter (PM) and forecasts predict that these harmful emissions will increase between 50–250% by 2050 [11].

1.2. Complexity Aspect

The new strict environmental regulations together with the continuous maritime transportation volume and emission increases, make the energy transition and transformation of ship propulsion systems to carbon neutral and ultimately operating in zero emission a necessary step. Interests in innovative, novel concepts researching into the implementation of alternative and renewable fuels, all-electric and hybrid power and propulsion energy (PPE) systems must gain momentum over the next years. The minimal prior knowledge in Zero Emission Ships (ZESs) generates several multifaceted challenges that cannot be confronted using only the traditional ship design approaches. This thesis identifies the following numerous important reasons:

Well-established Marine Fuels: The challenges presented in the development of zero emission PPE systems are far from simple. The well-established fuels used within the maritime industry for several years such as HFO have high efficiencies, attractive high-priority parameters (see Figure 1.1) and relatively low costs, making alternative choices highly unattractive [12].

For instance, an important fuel parameter is the energy density which can partly determine how applicable the fuel is for certain ship types and ship operations [13]. LNG has about 1/3 the volumetric energy density of diesel, when taking the storage system into consideration [13]. Liquid hydrogen, ammonia and methanol have significantly lower volumetric energy density of about 40-50% of LNG [13]. These increased volume requirements for accommodating alternative fuel energy carriers generate a PPE system design challenge for ZESs. New and innovative PPE system configurations, overcoming these challenges must be designed. In Figure 1.1, a colour scheme from green to red is used to represent key fuel parameters from best to worst respectively [13]. It must be noted that this is using generic information and in actual comparisons of fuels, details and specifics should be taken into consideration. Additionally, the production for LNG, LPG and methanol is considered from fossil sources and the fossil fuel data assume no Carbon Capture and Storage (CCS) process in Figure 1.1.

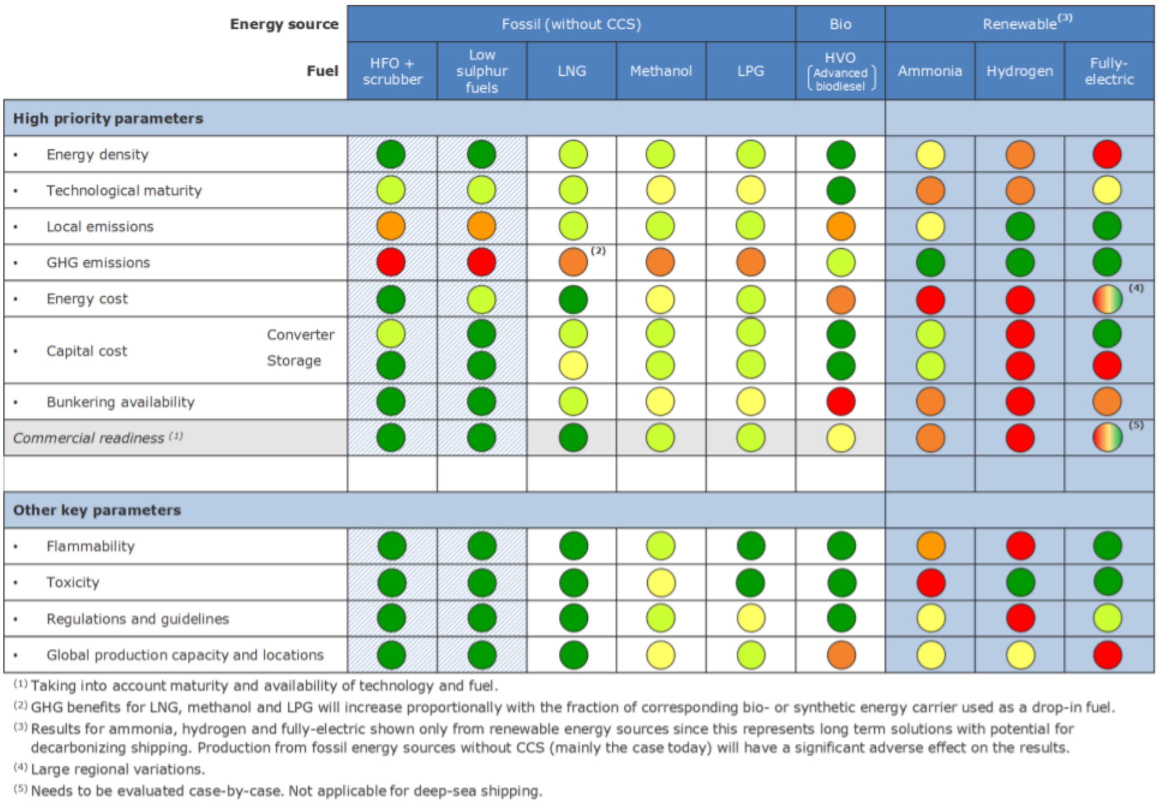


Figure 1.1: Comparison table of fuels. A color scheme is used for ranking from best (green) to worst (red). [13]

Furthermore, another difficulty towards the transition to new energy carriers, includes the challenge of not just replacing the prime mover engines but the technologies associated with all the auxiliary and supporting systems across the vessel [12].

Contextual Challenges: Traditional ship design practices are unable in capturing unknown future dynamic changes. These can include the uncertainties involved with future emission taxes and new regulations, unknown trends in alternative fuel advances and their supply [12]. Enhancements in ports infrastructures and the availability in bunkering of alternative fuels is essential to make innovative changes [12]. The new challenges raise complexity as the context around the ship must be included when looking for solutions. A helicopter view, capturing all data and variables is essential from the early design stages to tackle these problem and answer multifaceted questions.

Nowadays, when future proof concepts are designed, future possible scenarios need to be taken into account [1]. For example, today's access and the ability to work with alternative fuels is limited but in the near future it is expected that their easy access will be feasible. It might be methanol, hydrogen or any other alternative fuel. It is certain that there is going to be some energy change and is essential for the newly designed innovative vessel to take future scenarios into consideration and to have the ability to incorporate these necessary changes. It is important to start designing the PPE systems while having in mind future options, with different possible solutions. This stresses the importance of the newly designed PPE configurations to include the appropriate interfaces that would enable future elements to be connected. For instance, in the near future a diesel generator system must be considered that it might be replaced with a fuel cell. Therefore, when looking from a future perspective connecting the diesel generator to a DC distribution system might be selected instead of an AC distribution. Even if a diesel generator connected to a DC distribution switchboard requires an AC/DC converter, it enables the easy replacement of the diesel generator with a fuel cell in the future.

Levels of Fidelity: From the initial stages, for all engineering domains, numerous computational models of varying fidelities can be developed. High fidelity models, which can be computationally expensive can describe more accurately the problem by capturing more details, whereas low fidelity models that require lower costs are less accurate by taking advantage of domain expertise and in-depth knowledge [14]. This is clearly illustrated in figure 1.2.

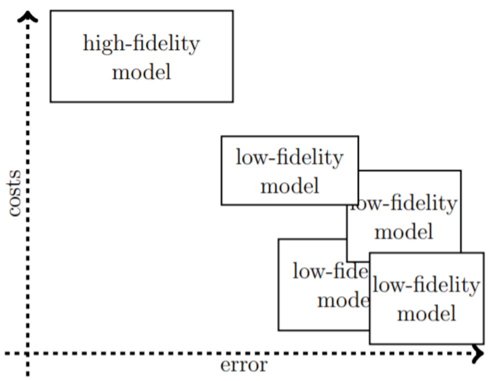


Figure 1.2: Low and High Fidelity against Costs and Error [14]

Within the traditional ship design it has been well known that the contribution of experienced naval architects and marine engineers is vital. The ship designers' expertise and the well-established designs within the industry enabled the traditional ship design from the early-stages to be based on low fidelity sources. During the early stages for the design of traditional and well-established ships, low fidelity tools are used within each discipline team, each concentrating on a specific sector and often ignoring all the other disciplines. For instance, a hull form can be simply chosen without identifying the various systems that must be included in the PPE system. A volume percentage is chosen and dedicated for the different systems and making sure that the required systems and cargo fits.

Knowledge and previous experience for ZESs and innovative PPE systems is very limited and the fundamental answers to challenges in terms of physics, new technologies and design are still unknown

[1]This paragraph includes conclusive outcomes from in-depth discussions with MARIN's supervisors Alex Grasman and Udai Shipurkar.

from the conceptual stage. Therefore, solutions cannot only be confronted using the traditional ship design based on low fidelity models performed individually from the different engineering discipline teams involved. For the design of ZESs with innovative PPE, the design again needs to start with low fidelity, however all the other disciplines cannot be omitted. As prior knowledge is minimal, it is essential to find a way where concurrent communication is possible during the early design stages between the different disciplines specialists. As the conceptual stage starts with low fidelity and prior experience is limited, several design changes will be involved as the design progresses. Therefore, the ability not to lock-in the early decisions and to have full traceability of the design changes throughout the process is highly crucial.

To gain insight and understand the specifics into the performance on novel vessels, high fidelity tools such as detailed mathematical model simulations are required which will have high computational costs [14]. These are performed gradually as the conceptual design stage progresses and knowledge of the specific design increases [2]. If high-fidelity tools are used directly in the initial stages without fundamental knowledge many assumptions will be required [15]. These assumptions will essentially lock in decisions early and unavoidably limiting the exploration design space of other feasible solutions [15].

Multi-Disciplinary Design: As the size of information involved in a ship design increases, the fractionalization of knowledge and information across different disciplines increase as well, making the whole ship design, a multi-disciplinary approach [16]. With ships becoming more and more complex its unlikely that one company has all the knowledge needed to design a ship. Nowadays, many different discipline companies are involved making the whole design procedure highly complex [16]. Over the years, the ”diesel engine world” became very mature and the diesel distribution system is well-established within the industry. However, moving towards ZESs with new PPE systems and with specialised distributions, complexity is increased. For instance, a fuel cell power system distribution increases the number of systems, sub-systems and interfaces involved. Expertise is therefore fragmented to different specialists. For example, the fuel cells manufacturer needs to exchange information with the ship designers for the necessary fuel cells interfaces such as the electrical installation system and the cooling support system. Moving towards the newer forms of power conversion and newer technologies, it becomes very important for all these different elements to have the proper communication during the design stage and in the physical architecture where many specialists are involved and this can be achieved through the proper digital models.

Additionally, with the increased complexity on board, the number of ship’s systems, sub-systems and interfaces involved increase as well [16]. For instance, Hybrid Propulsion Systems (HPS) which can include both electrical and mechanical systems to support different ship’s operational profiles and minimise emissions. HPS need to have robust prime movers and transmission systems to support and operate under different modes such as Power-Take In (PTI) or Power-Take-Off (PTO) [12]. An efficient Energy Management System (EMS), can become a challenge because it must be able to estimate the point where is the most efficient performance of the whole HPS and take automatically the necessary actions, keeping either the mechanical and/or the electric part of it performing [12]. Therefore, it is clear that the on board complexity is increased substantially and various discipline specialists are involved such as marine, electrical, mechanical and systems engineers. A clear communication from the initial stages of design of PPE systems between all the specialists is essential.

Smarter, Safer & more Sustainable ship solutions: Better development processes are needed as the need for more effective and more efficient solutions grow. This need occurs simultaneously with the trend of reducing manning and increasing levels of automation [16]. Nowadays, ship design aims at achieving efficient performances for the different mission types a vessel operates in. For instance, when looking at the design of a zero emission motor yacht, different operations with different requirements and different systems are involved. Missions include zero emission cruising nearby bays, ocean transiting where higher level pollution is acceptable etc. In the conceptual stage, choosing and designing these systems as efficient as possible is critical, as they can be implemented and installed in many different ways. More efficiency means more successful emission reduction. These choices include, from the exploration of different energy carriers, to choosing the specific type fuel cell up to the imple-

[2] From in-depth discussions with MARIN’s supervisors Alex Grasman and Udai Shipurkar.

mentation of Waste Heat Recovery Systems (WHRS), if found necessary, for reusing heat from one system to another. Moreover, the challenge has shifted from focusing just on the ship itself. Investigating the life cycle of a new-build vessel is critical and many new variables must be included. More awareness of a lifecycle approach is adopted from the early design stages which analyse the ship up to the end of its life, the demolition stage [17]. Rules from IMO became available, with respect to the ship's material used and the appropriate planning for ship recycling [18].

1.3. Literature Research Questions

The following literature research questions are formulated to be investigated and answered within the following sections. The literature research questions have the aim to help in identifying a main research gap from both literature and the industry. These will aid in formulating a main thesis objective and the main research questions, that will be presented in a later section, after answering the literature questions.

1. Why is the conceptual design stage critical in addressing the ZES challenge?
2. What are the limitations in the traditional ship design approaches for designing ZESs?
3. What is Model Based Systems Engineering and how can this methodology aid in handling the increased complexity of Ship Design?
4. What is the current approach within MARIN for the exploration and conceptual design of power, propulsion and energy systems and what is the role of the MBSE methodology?
5. What gap is identified from literature and the industry that can be addressed in this thesis and be the research objective?

The immediate technological progress needed within shipping and the multifaceted challenges that cannot be confronted only with the traditional ship design approaches have been established. In the following sections ship design will be investigated in detail. Firstly, the importance of the early design stage will be explained. The main ship design practice used for several years, Ship Design Spiral will be explored, providing the appropriate conclusions and identifying its limitations in addressing the complexity. At the same time, other alternative ship design approaches will be presented.

Additionally, to address the identified ship design limitations, an advanced and relatively recent design methodology derived from Systems Engineering (SE), known as Model Based Systems Engineering (MBSE) applied within MARIN, will be investigated. The methodology's current application within the ship sector design will be researched. Furthermore, the MARIN approach for exploration and conceptual design of power and propulsion energy systems will be elaborated. The research on these different topics will enable the identification of a suitable gap for the thesis project and the formulation of the appropriate main thesis research question.

2
Ship Design

It has been recognised over the years that naval architects and marine engineers are continuously confronted with numerous conflicting solution choices from early on, from the conceptual stage of ship design. Numerous interactions are involved between several subsystems that must be integrated together to form a ship, requiring a lot of fundamental understanding, excellent organization and careful planning from the early stages.

2.1. Design Terminology

Before investigating ship design in more detail, it is essential to provide the correct definitions of some important design effort components that will be repetitively used in the report, defined from literature [19].

- *Design Approach:* The underlying guiding principles of the design. This involves the starting guidance for the initiation of a design effort. For instance, should the design proceed in a sequential manner or should activities occur in parallel?
- *Design Process:* A structured sequence of steps for the implementation of the design approach. This is the framework were the approach is applied.
- *Design Method:* This is the specific way in which the approach within the process is executed, including how design alternatives are understood, analyzed and selected.
- *Design Tool:* Used for the support of the design methods and enables decision making with the provision of design information.

2.2. Conceptual Design Stage

In this report, emphasis will be given on tackling the unforeseen challenges of sustainable ZESs that require novel PPE system configurations described in section 1.2 during the conceptual early stage. Therefore, in this subsection the importance of the conceptual stage will be clarified, answering literature research question **1**.

Firstly, there is a major difference that distinguishes the early design stage from all the other stages for the development of any product or system. The early stage is involved with the elucidation of the appropriate requirements and the identification of the design problem instead of actual engineering design work [20]. During the conceptual stage the most important and costly performance-related vessel decisions are taken and it can therefore be considered as the most critical stage [21]. Figure 2.1 highlights the enormous percentage of costs committed during the conceptual stage which is about 70% of the total life-cycle costs. This is due to initial decisions taken, constraining further down the line the design choices. Therefore, it can be easily realised that incorrect decisions and defective designs would lead to significantly raised costs and unwanted consequences. The costs of repairing defects during the operating phase can be up to 1000 times higher than in the conceptual stage [22].

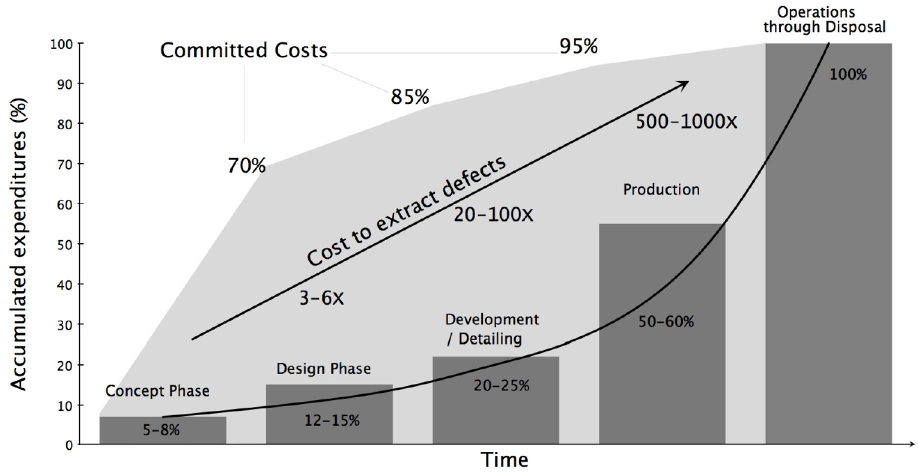


Figure 2.1: Accumulated expenditures in different phases [22]

Unlike the traditional shipping that greatly relies on 2-stroke or 4-stroke diesel engines with well established fuels and configurations, in ZES concepts there are many different possible solutions that require intensive exploration [23]. Different low/zero carbon energy carriers such as LNG, methanol, hydrogen exist with different possible system configurations such as internal combustion engines (ICE), Fuel Cells (FC) or batteries [23]. In the conceptual design of PPE systems for ZESs with limited prior knowledge, the optimal starting point cannot be predicted until higher fidelity models on later stages are performed, that can capture the dynamics. PPE system details such as power and volume requirements arise from results of higher fidelity simulations performed on later stages. Additionally, in the conceptual stage it is vastly common for ship designers to be faced with contradicting choices emerging from dissimilar priorities and motives from the different stakeholders [24]. For instance, for some stakeholders the investments costs might be more important than the operational expenses of the future. Additionally, the total elimination of harmful emissions emitted by the newly developed ship might be crucial for some owners but not for others not [25].

Alternative decisions on various ship parameters that are connected to several functional ship requirements have to be made. In the past decades the only important requirements for a shipping vessel were speed and payload capacity. Nowadays, numerous life-cycle performance requirements should be considered such as smarter, safer and environmental friendliness or flexibility, robustness and agility within technical, operational and commercial aspects [26], [27]. Nowadays, details such as the vessel's different mission types with power consumption profile charts and focus on the dynamics with power time charts are included as system requirements. These details can be combined with the ship's emission objectives from the conceptual design stage [28]. These requirements are either interrelated or conflicted with one another and careful criteria selection need to be made on the early conceptual design stage, highly affecting the total life-cycle ship performance [29],[30].

2.3. Ship Design Spiral

In the following sub-sections up to sub-section 2.8 the current design techniques will be overviewed including the current design limitations for ZESs PPE systems, addressing literature research question **2**.

Ship design within ship building has a very long history and several developments over the years. From the eighteenth century the first analyses were performed on fundamental aspects such as vessel stability [31]. Important material and technological improvements such as the replacement of iron with steel hulls and the introduction of steam engines, enabled bigger, specialised ships to be built [31]. As complexity grew and different operational requirements were developing, it was necessary for a ship design approach to be developed and offer technical solutions. In 1959 J. H. Evans was the first ship designer to address how to confront ship design complexity by introducing his book on "Basic Design Concepts" and his introduction on ship design spiral theory [32].

Ship design spiral is an iterative, multi-disciplinary process that extends for a long period of time. At the early conceptual stage, ship designers start with a selected solution and using low fidelity techniques the broad trade space is explored. As the design progresses to latter stages, fidelity increases and more detailed decisions are taken until a single design solution is obtained. During the design spiral, one design parameter such as resistance, weight, stability etc. is examined in a sequential and in an iterative manner until all constraints are satisfied and all requirements are met. The design spiral is considered to be based on a point-based design approach since each iteration aims to formulate a design to meet the requirements. Figure 2.2 portrays the ship design spiral introduced by Evans.

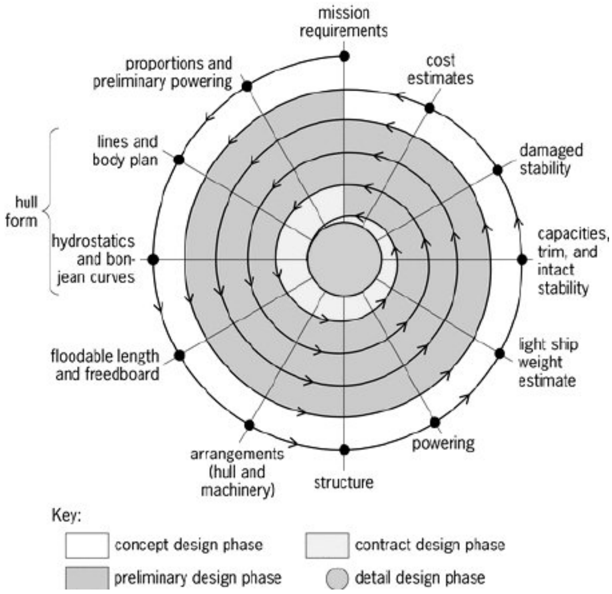


Figure 2.2: Ship Design Spiral introduced by J.H. Evans in 1959 [32]

The increased concerns of the environmental impact of shipping, the enforcement of new environmental laws and the improvement of computed-aided technologies further enhanced the design spiral process. Over the years, these driving factors led to the the improvements of specific disciplines tools such as CFD and FEM for hydrodynamics and structural analysis respectively and the necessity to assess the ship's lifecycle from the early stages [31]. However, despite these incremental improvements and additions throughout the years, the fundamental ship design spiral process has essentially remained untouched. Since its introduction this process dominates the maritime industry until the present [31].

Even though this process has been well-established in the maritime industry, many concerns are raised about its limitations in the conceptual design stage. As numerous questions are raised from the early design stages, the ship spiral is found to be unsatisfactory to deal with this complexity. As clearly stated in the original book by Evans the design spiral only deals with "how" to design and not "what" is required to be designed, involving synthesis and not necessarily including optimisation [32].

The spiral point based approach's final design solution greatly depends on the starting conditions. It does not assist in converging to the global optimum design if the starting point is not the optimal [24],[33]. In the point based approach, the starting point matters and there is no guarantee it will converge [15]. In the conceptual design of PPE systems for ZESs with limited prior knowledge, the optimal starting point cannot be exactly known or predicted. Many questions are present during the start of the design until higher fidelity mathematical models are performed. PPE system details arise from results of higher fidelity simulations performed on later stages such as different power and volume requirements. This can greatly affect the PPE system starting point.

Additionally, the process is mostly concerned with the vessel's engineering, as the main design choices are made in the preliminary stage. Little emphasis is given on the selection of the parameters chosen during the conceptual stage. The ship design spiral is found to be unreliable in designing new, novel and complex vessels [34]. In the conceptual stage, choosing and designing the PPE system as efficient as possible is vital, as many different configuration can be implemented. Emphasis should be devoted in finding the more efficient PPE system that would therefore reduce harmful emissions at the highest extent.

In the conceptual stage most well-established ship designs have a few clear design drivers and experienced ship designers are able to get many aspects correct from the first iteration in the early design [15]. The traditional powering systems using convectional diesel engine prime movers on board ships are mature and well-known within the industry. However, in ZESs with minimal prior knowledge, getting all the aspects correct from few iterations is nearly impossible and cannot be adequately addressed only by the experienced engineers nor using only the design spiral. Nowadays, numerous design drivers should be taken into consideration and investigated simultaneously from the conceptual design stage of the PPE systems. Some of the key design drivers include the different and demanding stakeholders needs and the ship's lifecycle aspect that can include prediction future energy carriers scenarios and therefore include the appropriate interfaces to accommodate future elements [24], [16].

The communication and cooperation between different disciplines in the preliminary stage is essential but the design spiral ends up in ”over the wall” type methodology, were documents are transferred from person to person after completion, with the possibility of context being transferred incorrectly or lost [15]. The ship spiral's sequential manner is limiting as PPE systems get highly complex, with increasing number of system and component interactions together with the simultaneous increase of different discipline engineers involved. The different domain engineers need to work concurrently with clear communication and early design changes should be continuously transparent for everyone.

It can therefore be concluded that the ship design spiral alone is nowadays considered insufficient for the increased complexity in the early development of innovative ZESs vessels. Necessary, state of the art design methods or tools are necessary to overcome the spiral's limitations.

2.4. Concurrent Design

A design approach that can address specific disadvantages of ship design spiral and improve the overall design of a system is Concurrent Design (CD). Starting for the early 1990s, this approach has been performed in several industrial sectors and mostly in the aerospace sector. Companies like the European Space Agency's Concurrent Design Facility (ESA-CDF) implement concurrent design for future mission feasibility studies [35].

The engineering practice of concurrent engineering is based on two key ideas. Firstly, all life-cycle elements must be in consideration from the early design phases including functionality, production, maintenance and environmental impact. Secondly, the design procedures should all happen simultaneously, enabling the identification of errors in the early design stages, increasing productivity and design quality [36], [37]. CD is a type of engineering practice where engineers perform and analyse design tasks in parallel. Massimo Bandecchi the CDF Founder stated: “Concurrent engineering involves bringing together all necessary experts into a single room to work together in real time” [35]. Concurrent engineering was expressed as a new and matured design management system and a precise systems approach for design optimisation [38]. As complexity in design increased CD became a commonly implemented technique.

RHEA Group, an international company for the provision of engineering solutions and system development, is a pioneer in the implementation of concurrent design. It has been identified by the company that for complex system designs CD application can reduce design completion time by a factor of four and cost by a factor of two. In cooperation with the Defence Materiel Organisation (DMO) since 2019, concurrent design is applied on complex projects, including the specification and purchase of new naval vessels [39] [40]. James White, a former US Navy helicopter pilot who currently works for NATO in the support of complex projects emphasised that with the implementation of CD, early design problems were solved, enabling NATO to deliver complex projects on budget and on time. Feadship together with ESA developed CD facilities to speed up and improve the yacht design process and add even more innovation flair to the company as raised communication by collocation decreases design time and reduces errors [41].

CD can help in the identification of the optimal global design, when proper digital models are used. For the appropriate execution of CD, digital models are essential, and one way of doing that is via MBSE models. Concurrency due to the increased number of different domain specialists involved from the conceptual design stage of PPE systems is critical. CD aims to include all ZESs' lifecycle elements from the conceptual stage and at the same time, the amount of systems and component interactions in PPE systems increase. Therefore, information involved are increased enormously and the proper coordination by having a way to digitally capture all these information from the different disciplines and share them with the designers is vital. CD can be achieved using MBSE methodology, explained in more detail in section 2.8.

2.5. Set Based Design

Both ship design spiral and CD are forms of convergence design where after several iterations, a feasible and balanced can be obtained [15]. The objectives of lowering the early decision costs and being more responsive to the owner's needs are not tackled by convergence design. However, Set Based Design (SBD), a different design approach enhances these objectives. SBD was developed in order to enable design decisions in the conceptual stage to be delayed and obtain a more optimum final design.

The fundamental objectives of SBD is to delay decisions until trade-offs and the implications of the design decisions are fully understood. The establishment of feasibility before commitment is critical and design decisions must be surely feasible before they are made. This design technique is helpful with changing requirements throughout the design process as no major decisions are taken from the early stages. The commitment costs are reduced from the conceptual stage and design freedom on a later stage is enhanced. Moreover, there is active communication throughout the process and the design efforts proceed concurrently like in CD [15], [33].

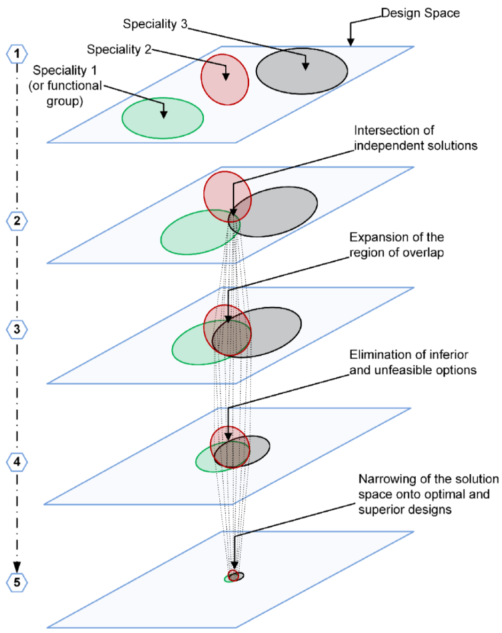


Figure 2.3: Set Based Design [42]

The large set of designs enables the coverage of a broader design space allowing the several trade-off analyses to be conducted. This early stage space exploration enables the easier identification of unattainable performance and costs from early on, with earlier knowledge on the design problem. Within set based exploration there are some key steps. Firstly, numerous concept solutions must be generated in order to cover many different design options and occupy the whole design and performance space. Analyses of these design options enable the early design insights on the problem. A selected number of solutions undergoes a further more detailed analysis. Using this design approach each discipline sector investigates the design region independently and identifies the best design space. The region where overlapping occurs between the different specialist areas, is the optimal for further exploration.

From an analysis conducted it has been shown that in the US, a shortage of design engineers has led to the appointment of many young and relatively inexperienced engineers as ship design managers. This transition can be seen as an opportunity to implement SBD in order to offer communication and information transfer to the younger engineers, augmenting their experience [33]. From various studies that have been conducted for SBD applicability in Ship Design it has been shown with SBD approach can be applicable in ship design community, replacing point-based design and a more globally optimal ship design solution is likely to be achieved [43], [44], [45], [46]. However, currently SBD is not used or investigated for the benefits it can have when being implemented in the design of ZES and PPE solutions. Due to the limited prior knowledge, design decisions and alternatives in PPE systems can greatly vary in the initial stages until more details are known on later stages. A method with the ability to document and determine from the start which factors will be unchanged and which will be volatile, can be very beneficial and aid in the design of ZES with innovative PPE systems.

2.6. Modular Design

Modularity is a modern systematic approach and quite dissimilar to traditional approaches. This involves the ship sub-divided into well-defined parts than can be recombined on a later stage [47]. Modular design is considered a general system concept continuum describing the degree to which a system's components can be separated and recombined [48]. This methodology involves the division of a larger system into smaller parts. The recombination of the parts that enables multiple end products to be developed is investigated through a set of rules given by overall systems architecture [49].

With modularity during the design stage, more efficient configurations process can be achieved tailored to specific customer needs based on ship product platform. Modularity is most suitable to be used when a design involves a flexible design and changing requirements that can be caused due to the changing market over time [50]. This adaptable design approach enables the exchange of modules throughout the ships lifecycle time to meet changing needs of the ship throughout its operation. The modular approach enables the basic and detail design stages to be executed on an earlier design stage, concurrently with the conceptual and preliminary stages due to the already designed modules [50]. The two design processes can therefore be executed concurrently, leading to lower design schedule times and costs. This increases the flexibility of the different needs and requirements stated by the stakeholders by easily and rapidly changing the design tailored to their specific needs [50]. This is clearly illustrated in Figure 2.4.

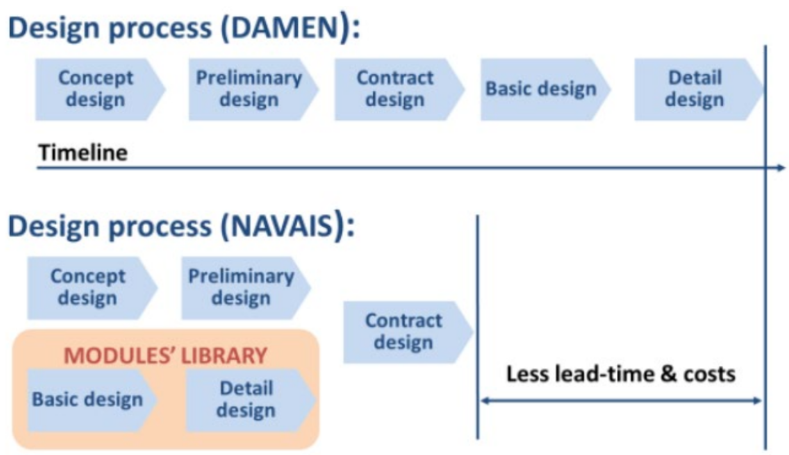


Figure 2.4: NAVAIS proposed idea, design flow process with modularity [50]

Actions have been recently developed for its implementation within ship design through the NAVAIS project. Part of an EU HORIZON 2020 project, New Advanced Value Added Innovative Ships (NAVAIS) is a large consortium consisting of various partners such as TU Delft, Damen shipyards and MARIN [51]. One of the main goals of this newly introduced project is to introduce and implement modular platform-based product families for Damen work boats and ferries. Modularity within the NAVAIS project facilitates both top down and bottom up approach for coastal passenger/cargo ferries operating at almost zero emissions and multi-use workboats respectively [52], [51]. From a top-down perspective a design project starts from scratch and strategically develops a family of product designs. In the bottom-up approach, the redesign starts from finished products in order to standardise components and improve economies of scale. This aims at formalizing the similarities in a group of family products and develop modules from the bottom-up, to create redeveloped designs [50].

Additionally, modularity can offer advantages in PPE systems for future ZES. Wärtsilä's uses the concept of modularity in the Two-Stroke Future Fuels Conversion platform, launched in 2022 [53]. This innovative and patented engine combustion technology platform enables the fast and cost-effective conversion of two-stroke main engines to operate on clean-burning future fuels. Successful initial engine tests were conducted in the Wärtsilä two-stroke engine laboratory in Trieste in collaboration with MSC Shipmanagement [53]. The platform design focuses on rapid retrofitting and attention is given to modularity, that will enable the switch to a different alternative green fuels or fuel blends when they become commercially available with a modest investment and minimal retrofit effort [53].

The modular architecture used for modularity method is only effective for product family designs and not for singular products, with performances typically compromised due to over-design [54]. In the current stage where minimal prior knowledge of sustainable ship solutions exist, emphasis on the effective designs of singular concepts should be prioritized. This method mainly focuses on tackling the economical benefits introduced by the increased competition in the shipping industry by exploiting economies of scale in an already well-known family product designs. Even though modularity is applied for almost ZE passenger/cargo ferries it cannot specifically be involved with detailed PPE systems design as it is mostly concerned with larger modules that aim to assemble the whole ship structure [54].

2.7. Systems Based Design

The System Based Design was introduced in 1991 and it has been used for the development of a large number of ship designs, mostly cruise ships and ferries [49]. Systems Based Design differentiated the traditional ship design spiral. The starting point of the design spiral as seen previously in figure 2.2 is a set of design requirements, demanded by the ship owner. These are known as ”over the wall” requirements for the ship designers, as most commonly they are unclear on how they were derived [16]. Nowadays, the ship owners together with independent engineering companies execute model testings and optimisations to analyse the behaviour of the owner's future ship and come up with the best set of solutions [16]. In this process there is a clear a gap between the ship owner who presents the problem and the shipyard's ship designers who try to solve the problem and design the desirable ship. Figure 2.5 depicts the region where the ship designer normally operates, often confronted at developing with the ship owner the operational concept. However, often it is just the requirements that are passed as a request to the ship designer. The operation in itself is the result of another set of processes quite often executed by ship owners assisted by independent engineering design bureau to generate some possible concepts as the owners recognise that for their next generation ships they must be more aware of the latest technologies available in the market [16].

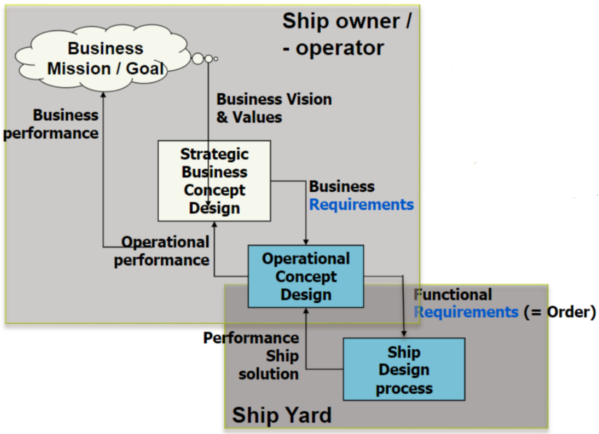


Figure 2.5: Design-to-Order perspective [16]

In 2009, Prof Kai Levander, understood that problem and modified by extending the spiral to clarify better from the starting point some crucial key aspects. This can be clearly illustrated in figure 2.6. This modification of the spiral aimed to establish the mission, the objective and the purpose of the ship from early on [16]. Understanding how the ship fits within an overall system such in a harbour infrastructure or as part of a larger fleet etc was important [16]. The basic design spiral by Evans quickly locked decisions from the first assumptions set by the naval architect and an approach to support innovation was essential [49].

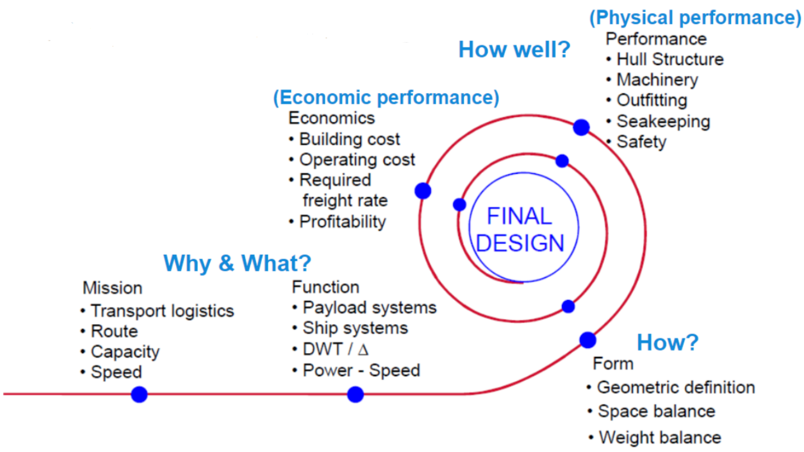


Figure 2.6: System Based Ship Design Spiral introduced by Levander K. in 2009 [49]

This approach should begin with the clear identification of a clear mission which describes the ship's tasks, capacity, operating area and performance factors [49]. Thus, the composition of the design steps is changed to defining the systems and functions followed by estimating the size and weight, selecting the ship's dimensions and evaluating performance [49]. The design spiral is “straightened” and the required loops to reach a design solution are reduced [49], [55].

Nonetheless, Systems Based Design and the corresponding spiral design have some limitations. The new designs developed are limited to already known designs as pre-defined geometries are implicitly used. Many data sets are based on information from regressions like the system definition, the geometric sizing and the weight balance and data [55].

2.8. Conclusions on Current Ship Design Approaches

In this report a description has revealed the current multifaceted challenges of novel, ZESs and how the predominant current ship design approach, ship design spiral, cannot solely address the enormous and unforeseen complexities presented. Advantages from other alternative ship design approaches have been presented. For instance, with the correct digital models, concurrency derived from CD during the conceptual design stages can be exploited to tackle PPE design complexities. The establishment of the ship's requirements with the function and mission needs are crucial in the conceptual design stage. In the traditional ship design spiral the set of requirements are "over the wall" derived from the stakeholders and passed on to designers. These initial discussions should involve both the stakeholders and the ship designers to achieve more effective designs.

The predominant ship design approach used nowadays, the ship design spiral depends greatly on the starting point, which for the case of ZES and more specifically PPE systems the starting point cannot be predicted, until higher fidelity models are performed. The spiral mainly focuses in synthesis and engineering work, with little emphasis given on the conceptual design stage. The early stage is involved mainly with the elucidation of the appropriate requirements and the identification of the design problems instead of actual engineering design work. Nowadays, numerous design drivers such as the dissimilar stakeholders needs, the life-cycle performance requirements, the essential operational flexibility require special attention. Advanced tools that can capture the complexities must be implemented in ship design. Requirement information must be integrated into the design process and progress tracked from the requirement item to the functional and physical design [52].

To address these issues, the application of Model Based Systems Engineering (MBSE) will be investigated. The MBSE is a methodology that will serve in the way in which design alternatives are understood, analyzed, and selected for a particular ship design approach, helping the designer's decision making [19]. The MBSE will not replace current ship design approach standards but will aid in enhancing them through the use of a centralized model repository and manages complexity [24]. The ability to capture and document the vast amounts of information from the initial design stages for the development of complex systems is crucial. In the context of Concurrent Design, considering all life-cycle elements from the early stages and the ability to concurrently work on several design efforts can be accomplished with the use of digital models. In the context of Set Based Design, determining right from the beginning which factors will be unchanged and which will be volatile can be critical. The development of a well-defined systems architecture, enforces structure in the stable elements and offers flexibility in the elements subject to change [24].

3
Model Based System Engineering (MBSE)

3.1. Origin and Definition

The theoretical roots of MBSE are developed from Systems Engineering (SE). Therefore, in the next subsections of the report, is necessary to provide a brief overview of the SE process and the fundamental approach it was derived from, Systems Thinking. Throughout the current chapter, literature research question **3** will be addressed.

SE is a theoretical framework originated from *Systems Thinking*, a generic approach that solves problems by viewing them as a part of larger overall system and not as a collection of parts that is the typical holistic approach [16]. Systems thinking is the ability to solve problems presented in complex systems and it has been defined as both a skill and an awareness [56]. Changing one part (or subsystem) of the system can alter other system's parts and therefore affect the whole system, with predictable patterns of behavior. The systems must be observed from a distance to include its boundaries, context, lifecycle and its behavior [57]. The International Council on Systems Engineering (INCOSE) provided a clear definition for SE interdisciplinary approach that enables the realization of successful systems [58]:

> "*Systems Engineering* emphasizes on defining customer needs, operational concept and required functionality early in the development cycle, documenting requirements. Design synthesis and system validation is then performed while the complete (lifecycle) problem is taken under consideration. (operations, cost and schedule, performance, training and support, test, manufacturing, and disposal). SE considers both the business and the technical needs of all customers with the aim to provide a quality product meeting the user needs".

In SE the lifecycle of a system is broken down into three principal stages; the concept development, the engineering development and the post-development [59]. The stages are broken down into sub-stages presented in Figure 3.1.

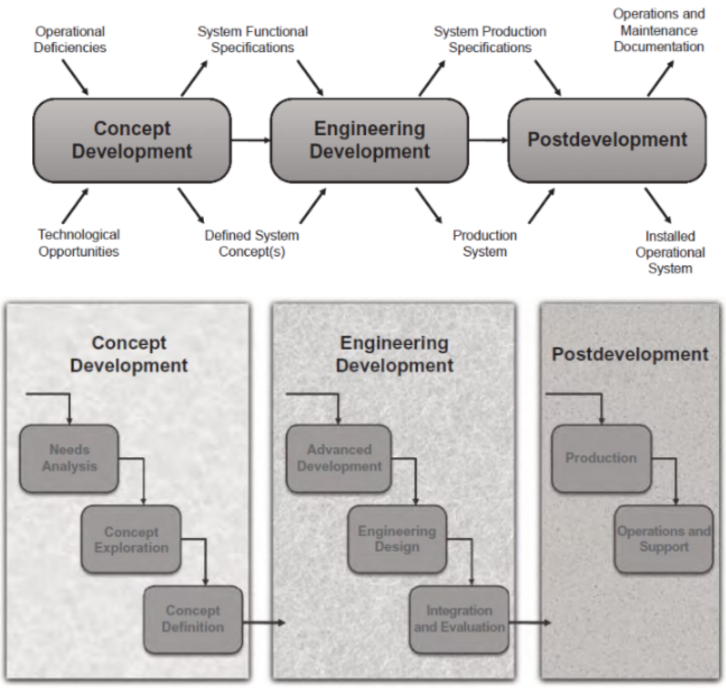


Figure 3.1: Systems Engineering Life-cycle Model [59]

In each of these stages a similar number of steps is performed, known as the general flow diagram. This is clearly illustrated in Figure 3.2.

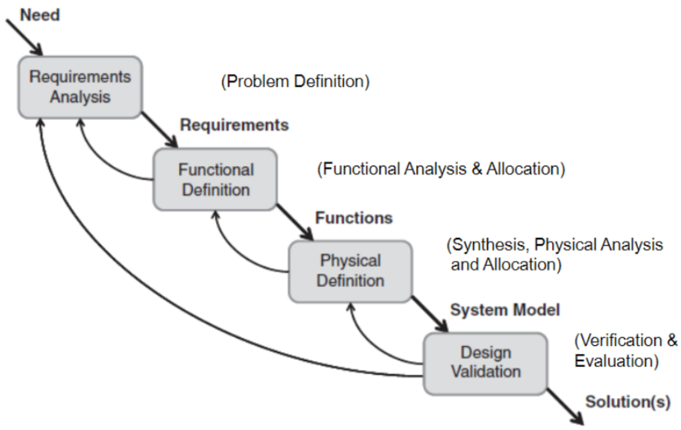


Figure 3.2: Systems Engineering General Flow Diagram [59]

The SE flow diagram starts with the requirement analysis where emphasis is given on what is needed and fully comprehend the problem. The functional analysis and allocation is then followed, where functions must be linked with the appropriate sub-systems. A component or a sub-system is very likely to fulfill more than one function [59]. For instance, a ship PPE system does not only participate in providing propulsion power for transportation, but additionally aids in the provision of required power to vital auxiliaries across the ship such as for liveability, hotel and routine services. That in itself, is another function. Then in the physical definition, the functions are mapped with the actual physical solutions after being defined.

Finally, verification is performed to check whether the solution meets the functional requirements and at the higher level validation is executed to evaluate how well the system solution fulfills the initial needs [59]. For instance, for a ZE cargo vessel at the highest-level, the major need and operational objective is the generation of profit. By defining actual scenarios, the profit can be estimated and performance and effectiveness evaluation its provided. This can better be visualised in a V-diagram shown in Figure 3.3. Systems engineering is often referred to as a V-diagram, which can be constructed by re-positioning the SE general flow diagram blocks [16].

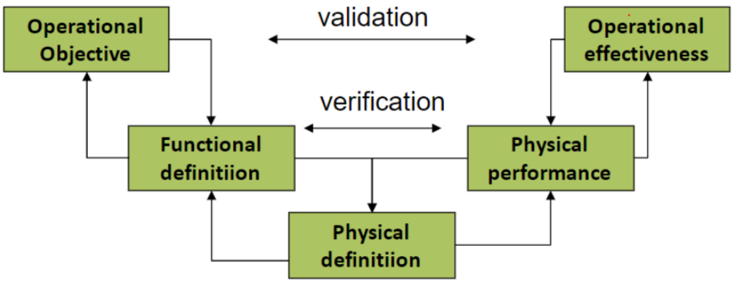


Figure 3.3: Systems Engineering V-diagram [16]

Many similar versions of V-diagrams can be found in the SE discipline literature, all based on the fundamental ideas [16]. V-diagram can be a better representation, showing the connections between the two side. The left side illustrates the breakdown from the high-level of the operational objective, to the functional breakdown up to defining the possible physical solutions. In this way the problem is broken down into manageable parts that can be solved [16]. The right side shows the integration of the total solution and the direct linkage of verification and validation with the functional requirements and operational objectives respectively.

Nowadays, the increased complexity in the ship design industry makes specialists to focus on systems engineering, deviating from the conventional design spiral. Ship design will merge with Systems Engineering (SE) process, with naval architects taking both roles [24]. At the same time, due to the increased complexity the digital-modeling environments such as the MBSE methodology are needed to capture and track the complexity [60].

MBSE brings together the framework of systems engineering based on the fundamental approach of systems thinking with the concept of a model [57]. A *model* is a simplified graphical, mathematical, or physical representation of something that abstracts reality to reduce complexity [61]. A model is the formal way in simplifying and representing a system. The system model must be represented with less detail until the system's structure and behavior are apparent and its complexity is manageable. In other words, models should sufficiently represent the system, and the system should confirm the models [62].

Over the past few years the digital-modeling environments are continuously increasing and this led to the increase of MBSE methodology as well. In 2020 NASA reported, "MBSE has been increasingly embraced by both industry and government as a means to keep track of system complexity" [57]. MBSE essentially takes the place of the traditional systems engineering documents with models in order to improve the development of complex projects [63]. MBSE estimates have shown that the total development costs can be reduced by as much as 55% [63], [64]. The methodology is used to support the development of highly complex systems with their requirements, design, analysis, verification, and validation and unlike document-centric engineering and places the model at the center of the design [57].

Unlike document-based systems engineering, a digital modelling approach like MBSE methodology can be used as a single source of truth for the system. The views and needs of the various stakeholders and the design proposals and solutions of the numerous discipline-specific engineers can be created using the same model elements and can be all captured under the same model [57]. This allows common standards system documentation that can be validated to remove all inconsistencies. MBSE improves the system analysis and lowers defects [57]. A digitalized system that is available for analysis across all the involved disciplines enables the consistent propagation of corrections and incorporation of new information and design decisions resulting is an overall reduction of development risks [57]. The formal definition of Model Based Systems Engineering (MBSE) according to INCOSE states [65]:

> "The formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."

3.2. Capella with ARCADIA Method

MARIN uses the MBSE methodology for the exploration and conceptual design of PPE systems which will be further explained in chapter 4. The MBSE methodology is implemented using Capella with Arcadia method. Arcadia is an easy to comprehend modeling method which has been developed and applied by Thales in 2011, supported by a dedicated tool software named Capella. The Capella tool with the Arcadia methodology enables engineers from various domains without a complicated transition to access the ”systems engineering benefits” and optimise the design process [66]. Arcadia aids in the definition and validation of the system architecture. It provides assistance to complex engineering design by using formalised models of operational, functional and physical needs. The key principles of Arcadia consist of [66]:

- All stakeholders share the same model information and methodologies;
- Each engineering specialization is formally linked back to the requirements for verification;
- Establishment of rules for early verification of the architecture;
- Use of co-engineering where joint elaborated models link and validate engineering at different levels and different specialties.

Arcadia methods consists of different levels of architecture [66]:

- OPERATIONAL ANALYSIS: “What the users of the system need to accomplish”
- SYSTEM ANALYSIS: “What the system has to accomplish for the users”
- LOGICAL ARCHITECTURE: “How the system will work to fulfill expectations”
- PHYSICAL ARCHITECTURE: “How the system will be developed and built”
- EPBS (End Product Breakdown Structure) AND INTEGRATION CONTRACTS: “What is expected from the provider of each component”

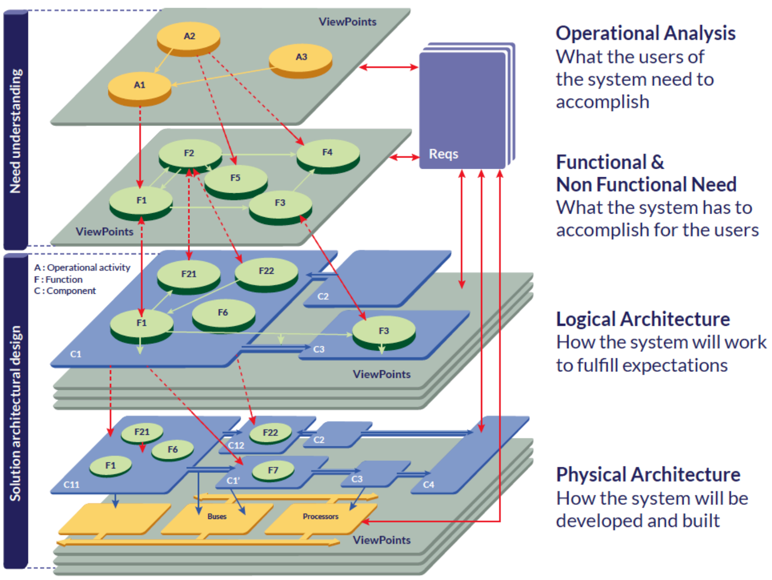


Figure 3.4: Arcadia Engineering Levels [66]

3.3. MBSE in Ship Design

Ship design complexity is bigger than ever before with challenges in the conceptual design increasing rapidly for naval architects. Recently, over the past few years MBSE has been investigated as a key implementation method to help addressing the complexity challenges in ship design.

Nadia A. Tepper explored the use of MBSE to develop systems architectures in naval ship design using Vitech CORE tool [24]. More specifically, the system architecture of the subsystem of propulsion system of a naval warship was developed. Through her research it was concluded that the MBSE can enhance communication between stakeholders by providing a single source of information, improve requirements traceability and decision making [24]. Additionally, architecture system models improve decision making processes, as decisions can be driven by real functional requirement, with the ship designers having the ability to see how one change can affect the whole design. It was observed that the traceability inherent in a systems model allows for more accurate change assessments and alternatives analysis [24]. It provided the ability to observe how one small change can drastically affect the whole design [24]. For instance, in the developed system architecture, a change in the prime mover can be investigated by observing from specific diagrams which functions and which inputs and outputs may be affected. It highlights in which functions the replacement must be performed and shows the data interfaces between the replacement component and the other elements of the system/context [24]. As observed from the system architecture, a change in the prime mover affects the ability of the system to generate mechanical energy, therefore affecting the engine break power, exhaust air, combustion air, fuel oil, and start air [24]. However, as stated by Nadia as ship design has deeply embedded document-centric nature of the ship acquisition process, the transition to MBSE would include a considerable amount of training in order to effectively use the system model and to maximize the perceived benefits of a model-based environment [24].

A PhD thesis was conducted by Corey Kerns for Virginia Tech University in 2011 to assess the helpful contributions of MBSE to improve and update the Multi-Objective Optimization approach to the ship design process [67]. The research determined that the MBSE methodology offered important benefits when implemented in ship design even though the research did not investigate implementation techniques. Firstly, the MBSE methodology offered the ability of the architecture to act as a single source repository for all data, guidance, design characteristics, functions, processes, cost, risk, effectiveness, and captured all of the relationships between these aspects making it a potentially powerful tool that can manage complexity [68]. MBSE was found to be very useful for organizing and understanding the ship Concept and Requirements Exploration (C&RE) and ship synthesis process [68].

In another research paper by Corey Kerns et. al. for Virginia Tech University in 2011, a method description for building a Design Reference Mission (DRM) composed of multiple operational situations required by the ship's mission was provided [67]. The DRM was defined using the MBSE method and a Total-Ship System Architecture was used to define and understand the relationships between various aspects of the ship design and their relationship to operational effectiveness. Systems Engineering approach using MBSE to the ship C&RE process was evaluated. By capturing the C&RE process into a single repository offered the ability to further comprehend the complex process [67]. The authors suggested that multiple ship design cases need to be evaluated and more research is required to determine if these tools add sufficient value to the overall process to warrant their use [67].

A paper from the Submarine Institute of Australia Science, Technology and Engineering Conference investigated the practical design approach of modelling a submarine subsystem architecture using MBSE methods with SysML software [69]. Again, it has been identified that improved design consistency, precision, traceability, subsystem integration, and design evolution were achieved using MBSE method [69].

In the maritime industry the innovative program NAVAIS discussed earlier which investigates the modular design process, is guided by the MBSE approach to support system requirements, design, analysis, verification and validation activities [52]. This starts from the conceptual design phase and continues throughout all life cycle phases. The MBSE approach is delivered by the 3DEXPERIENCE platform which follows a V-systems engineering model. An innovative procedure known as ”modular system engineering-based ship design” is used to organize products into modular architecture, containing all relevant function description to satisfy the overall product purpose [52]. This procedure is based on the MBSE methodology taking into account the modularization aspect [52].

It can be clearly identified that MBSE offers great complex system design benefits however, compared to other industries the maritime industry has been traditionally less prone to innovative technique implementations. Literature on the application of MBSE in the maritime sector reveals that it has been limited to only a few research papers mostly concentrating on naval vessels and with only minimal exposure in the maritime sector. Minimal efforts for the utilization of MBSE benefits have been addressed for novel ZESs. Maritime companies discouragement for innovation has been the result of the extremely high vessel capital costs required and complicated design regulations within the maritime industry [70]. In the previous decades, the continuous increase in the vessel demand and the self-centric mentality has caused innovation to be incremental and slow within the industry [71]. The imminent need for innovation change and urgent requirement in developing novel ZESs, makes the MBSE an attractive methodology to be implemented in the ship design process.

4

The MARIN approach for Exploration and Conceptual Design of PPE Systems

4.1. Background

This chapter investigates the literature research question **4**. The energy transition and decarbonisation of the maritime sector is well underway. IMO regulations make necessary ships to operate with zero emission, creating many business opportunities [72]. However, challenging general and industry wide questions are developed and MARIN seeks to answer these questions [72].

- What will be the best clean fuels of the future?
- How energy will be stored on board, distributed and managed?
- Which power system will impose itself and fulfil the ambitions?
- Which bunkering will be available in most harbors?

MARIN has developed a concept tool SPEC (Ship Power & Energy Concept tool) to enable the investigation and comparison of different energy carriers and power conversion systems for the development of PPE systems. A Zero Emission Lab (ZEL) was developed by MARIN to enable the realistic testing on different operational profiles of promising PPE systems. Simultaneously, numerical models of the PPE systems will be developed and tested in the Virtual-ZEL. The V-ZEL can use time simulations, to investigate the performance under dynamic conditions.

The MBSE methodology will be used throughout the project to support the technical artifact and ensure clear traceability from operational requirements up to the engine room solutions. MARIN currently applies MBSE using the Arcadia method with Capella tool for the concept design of PPE systems. Arcadia with Capella tool is used to mitigate the risks of applying juvenile solutions and enables the lifecycle support of the ship's PPE system [28].

4.1.1. MBSE Role and Life Cycle Support

MBSE is used to support the lifecycle of the PPE systems and the initial concept design stage is divided in two categories; the exploration and the concept design. This can be depicted in Figure 2.5.

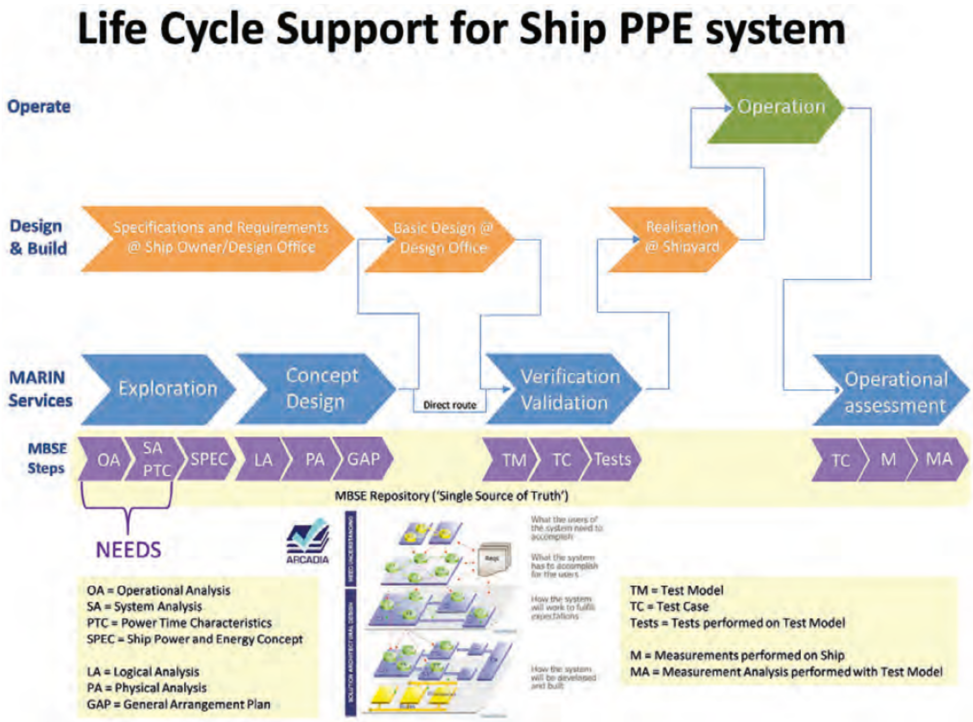


Figure 4.1: MBSE support the life cycle of a ship's power, propulsion and energy system [28]

The exploration begins with the needs analysis which consists of the operational architecture, systems architecture and the Power Time Characteristics (PTCs). The MBSE methodology begins with a system design, where using low fidelity, all different systems are included and taken into consideration and during the needs analysis no solutions are generated. PTCs represent the properties of the power consumption in time for the propulsion and auxiliary categories. These include the Mission Power Time Charts (MPTCs), the Event Power Distribution Tables (EPDTs) and the Event Power Time Charts (EPTCs) [28].

These detailed power properties are all connected to the Capella model as system requirements to the power exchanges in the system architecture. The MPTCs and EPDT of a specific use case are manually synthesised, using measured data and experiences from past projects [28]. The input comes from the group of participants of the use case. The use case is divided into specific, few mission types. An operational year of a vessel mainly consists of a certain number of those mission types [28]. A mission type is a typical standard mission that is regularly performed by the vessel and has a time step of minutes up to an hour. More details of these detailed power properties applied on a specific case study ship are provided later in the report, in section 7.4.1. Finally, the results of the power time analysis of the mission types are combined with the emission objectives [28].

These needs are input for the next step, the SPEC analysis which is the next and last task in the exploration phase. Details on how the SPEC concept tool works will be provided in section 4.1.2. When the exploration phase is ready and the SPEC analysis is complete, then the concept design phase will be executed with the SPEC results as an input. For instance, SPEC tool enables the identification of the system through a coarse first analysis including few inputs such as the ship's average power required, endurance etc. A first approximate of what is needed is known from the SPEC results and once a solution is consolidated, further exploration with higher fidelity methods can be applied. That is where conceptual design begins. The conceptual design phase involves the logical architecture, the physical architecture and the General Arrangement Plan (GAP).

SPEC aids in the first physical architecture by identifying the needed PPE system's building groups. This enables the initial low fidelity physical architecture with coarse calculations and on a latter stage optimisation models can be used to aid in the structure of the PPE system. For instance, following the

SPEC initial and low fidelity analysis, optimisation methods can identify higher fidelity details such as the number of fuel cells and batteries required within the system and their specific rating, the number of battery of this rating etc. This higher fidelity helps you refine your physical architecture with new information. At the same time the MBSE tools allow traceability, capturing all these necessary changes throughout the early design process.

For example[1], after SPEC analysis a 1200KW fuel cell is identified to be needed. However, on a latter stage with high detailed mathematical optimisation model that can capture the dynamics higher fidelity results can be obtained. More refined results can show that 3 fuel cells of 400KW each and 3 cooling inlets of 400KW capacity are a more optimal configuration. This is after the first refinement. For higher level of fidelity we use higher level of fidelity mathematical models to lead to higher fidelity physical architect. MBSE makes sure that the effects of all these changes are presented and indicates the further and necessary changes that have to be made.

4.1.2. Ship Power and Energy Concept Tool (SPEC)

It is considered necessary to provide a description of how the SPEC concept tool developed by MARIN operates within the ZERO JIP. SPEC tool enables an extensive comparison of power concepts of various configurations consisting of different energy carriers, power systems, after treatment data and other related power systems to be performed. Multi-criteria analysis is used in order to compare and rank the different possible PPE systems [73].

PPE Building Blocks: This generic platform was developed to capture all the different possible configurations including the power and propulsion system and the included auxiliary components, broken down into different building blocks [73]. As clearly seen in figure 4.2, the different building blocks that make up the PPE system are presented. The first building block is the *energy carrier block* that includes the energy carrier in its stored form on board. This block takes into account the fuel energy density, how the fuel is stored on board and the compression power it needs if found necessary, for its compression system. Additionally, within this block the shore grid requirements if needed, are taken into account together with the required electrical energy storage for batteries or super capacitors. The second building block is the *pre-treatment block* if necessary, for the fuel to be reformed before being used. The *energy conversion block* includes the prime mover of the ship for propulsion and the generators or fuel cells needed for the auxiliary power. Moreover, the *after-treatment block* includes the necessary power components required when exhaust gases formed that do not comply with the environmental regulations such as IMO Tier III or EU stage V for inland shipping. Lastly, the *power distribution, converters and drives block* takes into account how the power is distributed from the converters to the shaft and how energy is distributed to the hotel loads for the users on board. In this block various differences can be identified in different power ship systems configurations such as in a full electric and direct driven ships and is considered to be a vital design block [73].

[1] This paragraph includes conclusive outcomes from in-depth discussions with MARIN's supervisors Alex Grasman and Udai Shipurkar.

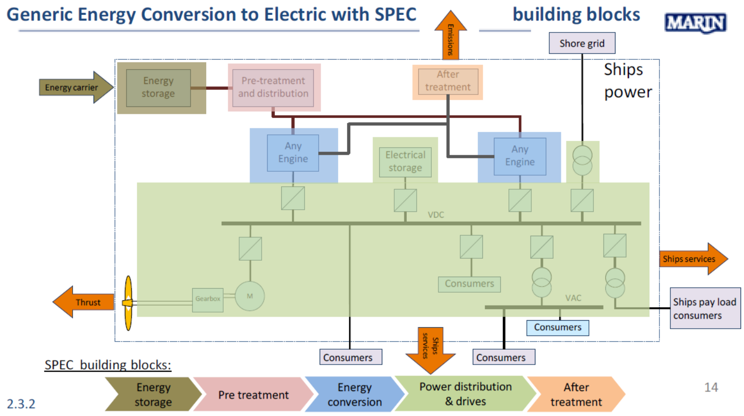


Figure 4.2: PPE different Building Blocks [73]

Comparison of different building block configurations: Various parameters are collected from the different building blocks such as energy density, emission information, operational and capital costs, power densities, chain efficiencies etc [73]. This enables the correct comparisons between all the different energy and power systems. For the energy carriers, databases capture all necessary features ranging from energy density, contained energy density (including the insulation surrounding the fuel), emission factors from Well-to-Tank (WTT) and Tank-to-Wake (TTW), CAPEX, OPEX and so on. For establishing solutions the energy carrier is combined together with all the other building block energy systems. Multiple solutions of an individual energy carrier can be obtained by combining different building blocks. For example, LNG can be converted and used in a combustion engine or it can be reformed and used in a fuel cell. All the final solutions are provided with several specific parameters such as total energy and power density, chain efficiencies, emission factors etc [73].

Pre-selection phase: SPEC design tool consists of a pre-selection and a design case and this is illustrated in figure 4.3. During the pre-selection phase, key performance parameters are identified, such as the installed power, the average power consumption, displacement, draft, gross tonnage etc. Additionally, ship's objective parameters are provided to the tool such as endurance, lifespan, only zero emissions profile and so on. Once these parameters have been identified, a selection of all the different possible solutions complying with the chosen criteria are provided. These solutions are compared in different parameters such as emissions, energy costs relative to a base concept. This base concept is usually a reference ship sailing on diesel, which is still the most common category of nowadays ships. This enables the extensive comparison between an innovative sustainable newly designed ship against a well-known design of a diesel vessel.

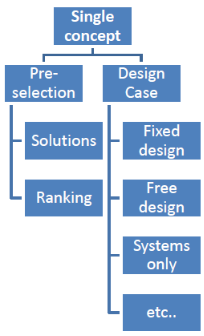


Figure 4.3: Pre-Selection and Design Phase [73]

The solutions can be then ranked based on weighting factors defined by the stakeholders on what is considered to be of greater importance. The numerous weighting factors are subdivided within two categories, technology & investment and operations. These two categories are then weighted against each other as it depends on the stakeholders decision of what is of greater importance, the initial investment or the operations during the lifecycle of the newly designed ship. This gives the freedom to the ship owner to decide on important choices and according to his priorities, solutions are ranked differently. An example of all weighing factors for technology & investments is shown in figure 4.4. In this example the criteria are weighed almost evenly. As seen in figure 4.4, the results can be presented as a table with a colour scale from green to red from best to worst solution respectively. Additionally,the Total Cost of Ownership (TCO) against different emission scenarios can be plotted within the SPEC tool. A CO_2 emission cost per tonne emitted can be chosen, for future possible scenarios comparisons. The higher the cost per tonne, the more the low carbon solutions will be favoured. The current CO_2 emission cost is about 28EUR/tonne and future predictions with higher costs can be visualised, predicting future comparable trends among the different energy carriers systems provided within the platform.

Configuration	Overall solution: Harmfull exhaust emissions	GHG emission	Solution score: summed	scaled
CNG Fuel Cell Electric	9	2	4,27	1,0
LOHC Fuel Cell Electric	9	9	4,35	1,2
LH2 Fuel Cell Electric	9	9	4,48	1,6
CNG ICE Electric	7	2	4,56	1,9
NH3 Fuel Cell Electric	9	9	4,62	2,1
NaBH4 Fuel Cell Electric	9	9	4,78	2,5
CH3OH Fuel Cell Electric	9	9	4,96	3,1
CompH2 Fuel Cell Electric	9	9	5,01	3,2
Diesel ICE Electric	6	1	5,57	4,9
Diesel Hybrid ICE Electric	6	1	5,57	4,9
Diesel ICE Direct	5	1	5,78	5,6
LNG ICE Electric	7	2	5,95	6,1
NH3 ICE Electric	8	9	6,38	7,4
NH3 Hybrid ICE Electric	8	9	6,38	7,4
Li-NMC Battery Electric	9	9	6,66	8,2
CH3OH ICE Electric	8	9	6,87	8,8
CH3OH Hybrid ICE Electric	8	9	6,87	8,8
DME ICE Electric	8	9	6,92	9,0
DME Hybrid ICE Electric	8	9	6,92	9,0

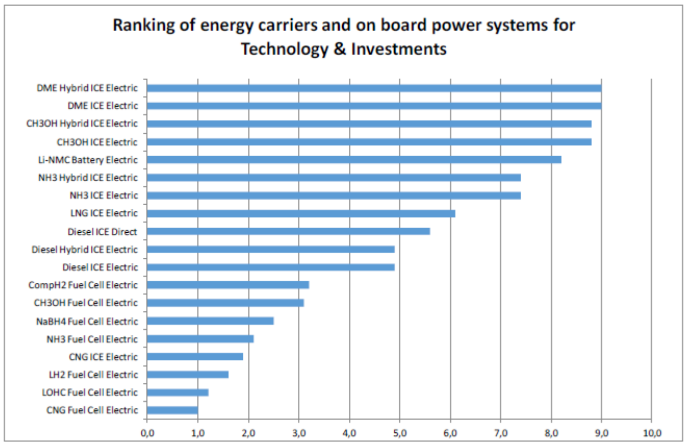


Figure 4.4: SPEC Ranking Solutions Results [73]

Design Case: Following the concept selection, the SPEC design case investigates the impact of the system concepts on the main particulars of the ship such as speed, payload and power can be determined. These parameters can be tuned according with benchmark vessel that MARIN is involved with. This enables the realistic assessment of the application of the power system solutions on board according to the specific mission and the specific parameters of the ship. Additionally, the operational envelope of the ship can be described. There are three main design cases, speed fixed, power fixed and speed free, all with different variants. For instance, when a fixed speed input requirement is selected, a design will be adopted based on the fact that the ship speed cannot change. A total of 8 design variants cases are obtained, with different combinations of speed, power, payload, displacement and different dimensions for several investigative comparisons.

5 Gap and Thesis Objective

5.1. Gap

This chapter addresses literature research question **5**. The MBSE methodology has been elaborated in detail. The benefits it can offer both in the early design stages and throughout the life cycle support for ship design have been addressed in literature. Specifically for ship design, the MBSE is found to be promising however, the advantages have only been investigated for the development of the operational and functional architecture in a few research papers [24], [67], [68], [69]. In this thesis report the MBSE advantages that can be obtained from the physical architecture and the generation of initial PPE system layouts will be investigated for the first time. Moreover, the investigation of the MBSE methodology in ship design in literature is limited only for the application of naval vessels which are known for their acquired complexity. In the current report, the MBSE promising benefits will be explored when dealing with the increased complexity of designing ZESs with juvenile PPE system solutions. Even during a period where immediate change in the direction towards sustainable shipping is required, the maritime industry is placed in a negative light in terms of its pace and eagerness in adopting new design approaches to deal with the increased complexity compared to other engineering domains. Most industrial benefits have been drawn from actual implementations of MBSE methods within different industrial sectors such as aerospace, defence, space and rail [74], [75], [76], [77], [78].

Additionally, SPEC tool and its important role alongside the MBSE methodology during the exploration phase has been thoroughly discussed and how the ship design efforts are guided up to the detailed MBSE physical architecture in the conceptual design stage. However, these formulated physical architectures of the specific use case vessels do not contribute to the spatial arrangement layouts that must be produced during the conceptual design stage. A clear gap can be identified between the MBSE physical architecture and the PPE system layout plans that must be generated. The transition from the MBSE developed PPE system's physical architecture to the geometrical description and modeling of the actual PPE system is missing. The initial PPE system layouts generated during the conceptual design stage using the MBSE derived information as inputs are missing and have not been explored. These layouts can contribute to important design geometrical and spatial insights that cannot be solely provided from the details depicted in the MBSE physical architecture. Several physical properties of the numerous building groups and their interconnections can be captured within the MBSE physical architecture but their geometrical analysis is missing. As clearly described in section 2.2, these insights are essential to be provided in the conceptual design stage, the most critical stage. The PPE system layouts generated early, can provide ship designers with contradicting and alternative design choices that must be taken. With the implementation of MBSE that can act as a single source of truth, digitally capturing all design PPE system details from the operational analysis, all these alternative choices and their impact can be now fully traced and help designers make justified decisions.

Bridging this gap requires extensive efforts and this thesis aims at adding the first stepping stone for the creation of this important connection. More specifically, this thesis will investigate the implementation steps in the conceptual stage needed for the proper transition from the MBSE physical architecture to the general arrangement plan (GAP) configuration. Investigation of the data inputs required from the MBSE physical architecture of a PPE system that would aid the General Arrangement Plan is essential. MBSE can track and identify the optimal physical system components needed however the spatial arrangement guidance and the physical interfaces between them needed for the actual arrangement visualisation are missing.

5.1.1. Research Question

After identifying the clear gap in literature and the maritime industry the following research objective will be pursued to be addressed in the next parts of the thesis.

- **Create a proper transition from the MBSE physical architecture to the geometrical description and modeling of the actual PPE system's General Arrangement Plans (GAPs) that can aid in the spatial guidance during the conceptual design stage.**

The formulated research objective that will be addressed in this thesis report, generates the following research sub-questions that will be answered in order throughout the report.

1. What modelling methodology and solution approach can be found on literature that can appropriately describe and generate a novel PPE system General Arrangement Plan (GAP)?
2. How will the tool's detailed methodology be structured and how will the results be presented?
3. Which Use Case ship and which novel PPE system will be investigated?
4. What type of testings will be performed and what design insights can be obtained from the generation of these initial GAPs?
5. How is the developed design tool validated, what are its current limitations and how are the generated PPE system GAPs compared?

The questions pursued to be answered within this MSc Thesis, will be supported by a specific Use Case within MARIN. The MBSE physical architecture of a specific Use Case will be used. However, the answer of the research objective will hopefully contribute in a higher level understanding on how the MBSE physical architecture should be formulated within general ship design efforts of ZESs and PPE systems. The research questions aim to investigate to what extend the MBSE can aid in the PPE systems' layout arrangement. These answers aim in further enhancing the MBSE implementation specifically for the maritime industry for future applications.

5.1.2. Method Requirements

As seen the MBSE methodology can aid in the development of the physical architecture in the conceptual design stage derived from the stakeholder needs after taking the appropriate decisions. However, the physical architecture has never been linked to modelling tools that aid in the appropriate general arrangement plan. MBSE can track and identify the optimal physical system components needed however, the spatial arrangement guidance and the physical interfaces between them needed for the layout visualisation are missing.

The gap is now described and the solution of creating a methodology for a design tool that can generate the PPE system layout accommodated within the machinery space is identified. The tool needs to work as an extension to the MBSE physical architecture and SPEC tool. During the conceptual design stages, the arrangement design tool needs to be able to use the level of detail captured within the MBSE physical architecture to create initial and feasible General Arrangement Plans (GAPs) of the novel PPE system within the predetermined engine room of a specific use case. A list of method requirements in order to meet the thesis' objective and provide an answer for the research questions is provided. These requirements can be divided in two main categories, what should be obtained from the MBSE physical architecture and what the formulated PPE system GAPs tool should handle.

From the MBSE Physical Architecture:

- Contain an adequate database of different PPE system building groups.

- Capture a sufficient number of physical properties for the concept design phase.
- Capture all the critical physical properties that will aid in the conceptual design phase.
- Include the necessary interaction between building groups.
- Ability to incorporate important design arrangement rules.
- Ability to input new building groups and/or more detailed physical properties of components in the future.

PPE system design methodology tool:

- The easy implementation of different Use cases and different PPE systems for different future testings.
- Ability to detect and handle interaction between building groups.
- Ability to incorporate important design arrangement rules and meet the minimum component requirements.
- Exploration of the solution space to aid in the formulation of an initial PPE layout in the conceptual design stage.
- Generation of various alternative arrangement layouts for the appropriate trade-off analysis.
- Be technically feasible and visually represented.
- Ability to be used by other engineers in an open and responsive way.
- Presented in clear and presentable manner for stakeholders and different domain engineers.

6

Solution Directions

Firstly, it was important to explore and identify the most appropriate modelling method for the PPE system. In literature the design tools specifically aimed for the ships' machinery room arrangement are very limited. Therefore, a more broad look for inspiration into the design tools concerned with the whole ship layout was found necessary. Furthermore, after identifying a suitable modelling methodology it was necessary to find a suitable resolution approach for generating the General Arrangement Plans (GAPs). Therefore, this chapter investigates the formulated research sub-question **1**.

6.1. Modelling Approaches

In literature the design tools investigating ship layout generations can have different fundamental characteristics. For instance, these characteristics can include the tool's required input level of detail and the tool's focus on the generated layouts whether is based on area, volume or even networks. Most design tools focus on naval vessels as they are considered complex specials and early insights are considered essential. Therefore, several of the ship design tool studies outlined in this section are not publicly available and details are limited, since they are mostly tested for navy application and therefore their content is not accessible.

6.1.1. Functional Building Block (FBB) Approach

A good chronological starting point can be the early stage ship configurations that were first researched in 1997 by D.Andrews and C.Dicks in an approach known as 'Functional Building Block' [79]. FBB is used to represent volume blocks of multiple spaces with a low level of detail that serve a common functionality. For instance, an accommodation functional building block can be represented by multiple cabin spaces (e.g. an accommodation FBB might represent multiple cabins). Andrews and Pawling used functional building blocks to describe the ship's geometrical, numerical and other characteristics [80].

Functional Integrated Design Exploration of Ships (FIDES) is a ship synthesis model used by the DMO during the conceptual design stage [81]. FIDES utilizes the FBB approach for the spatial arrangement of warships [81]. The level of detail can differ between different functional building blocks. For instance, much greater detail can be included for the functional building block that consists of the engine room, with object details accounting for components such as the engines and auxiliary components. In contrast, the functional building group corresponding to the accommodation areas can have much lower detail. Two examples of warship concepts modelled in FIDES are provided in figure 6.1.

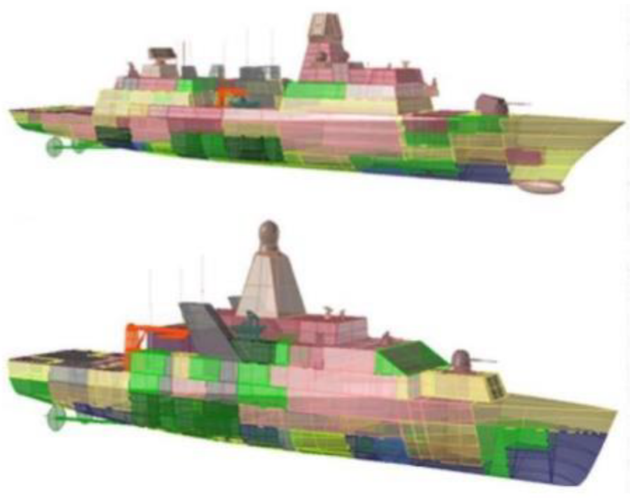


Figure 6.1: FIDES with FBB approach [81]

The application of FBB approach as it is seen with the FIDES tool, cannot be easily used for the engine room layout generation tool. The allocation of spaces into blocks of the same function cannot be realized on the results obtained from the MBSE physical architecture. The layout tool to be developed must deal with numerous different and unique building groups that have different functions and cannot be grouped as functional building blocks.

In the engine room arrangement the compartments are not yet defined and their required size is not determined. More detail is available from MBSE physical architecture where the detailed function of each individual building group is defined, but not in terms of compartments. In a way the FBB approach is more conceptual as the spaces within the compartments only require minimal information such as just the volume and necessary aspect ratio. For instance, the accommodation area building blocks, are represented with less detail using the estimated required area, based on naval standards and the required manning [81]. A margin is used to account for the additional access area needed such as hallways and staircases. Other functional building blocks can be volume driven. These can include on-board tanks such as fuel and water tanks and specific systems like cranes or sensor systems [81]. Different requirements are necessary to determine those compartments than what is necessary for the PPE system and the engine room arrangement. For the PPE system arrangement more detail information is essential. For instance, the numerous building group connections, their exact locations of input and output points and the required clearance spaces around each building group are just a few examples of the details that are necessary to be captured before modelling appropriately the PPE system within the engine room.

6.1.2. Packing problem

Another approach for the exploration of arrangement problems mostly focusing on volume requirements, is the Packing Problem. Packing problems are a broad class of mathematical optimization problems involving the attempt to pack objects together into containers or any space. A complete overview of the different packing problem variations was provided by Dyckhoff [82].

The packing problem methodology was applied in ship design by Van Oers who used a geometric packing as the basis for the parametric ship description [83]. The focus in this PhD study is on the whole vessel instead of a single room, such as the engine room but still there are clear similarities in the problem. This was based on two simple observations. First, all objects overlap completely with a larger positioning space (i.e the size of any ship is finite, meaning it can be enclosed in a box of finite dimensions) and all objects prevent unwanted overlap among themselves (systems cannot occupy the same space at the same time) [83]. These two observations are key characteristics of the packing mathematical problems as described above. A simple geometric packing problem is fundamentally similar and share the same key problem of packing objects in a positioning space with a much more complex ship packing problem. This can be clearly illustrated from Figure 6.2.

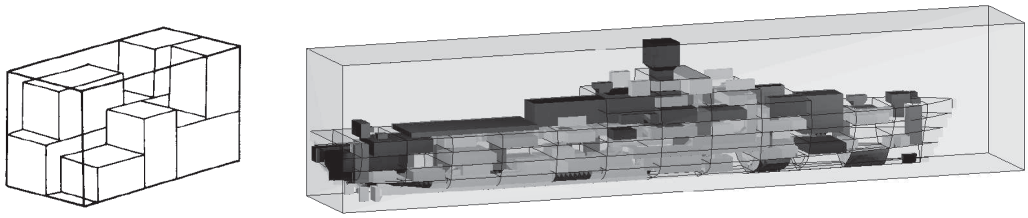


Figure 6.2: Comparison between a simple packing problem from Dyckhoff (left) and a complex ship-related packing problem (right) [83]

The ship design tool created by Van Oers during his PhD, automatically generated numerous three-dimensional ship design arrangements to improve the early stage design process decision making. The geometric packing approach for modelling the problem was used in combination with a developed search algorithm that could explore various feasible arrangements throughout the solution space.

Based on van Oers PhD research and his novel method, Duchateau (2016) improved the concept exploration process during the preliminary design of complex ships by creating the Interactive Evolutionary Concept Exploration Method (IECEM) [84]. The proposed approach, integrated three basic steps, First step was the generation and assessment of the performance of the design concepts, secondly the exploration and analysis of good performers and problem insights and finally by gaining more insight to be able to select the most appropriate design concepts for further analysis. Basically, the designers could now interactively guide the exploration efforts during the generated design concepts. Hence, this approach improved the conceptual exploration during the early design stage and lead to better requirement elucidation when looking at design solutions.

However, despite their usefulness these design tools using packing approach are both PhD researches. They are highly complicated, with thousands lines of code and it has been found impossible to further build upon these novel methods within a short Masters thesis timeframe. Additionally, FBB approach is applied for the parametric modelling and description of these studies and it has been found that it can have limited applicability for the generation tool of novel PPE layouts obtained from the MBSE physical architecture.

6.1.3. Intelligent Ship Arrangement

Contradicting, FBB and Packing approach that aggregate a sum of spaces (blocks) of the same function into compartments, a different approach known as Intelligent Ship Arrangement (ISA) was developed to place spaces individually into compartments for the ship layouts by the University of Michigan [85], [86].

These spaces are placed inside a predefined arrangement with fixed dimensions and predetermined position for decks and bulkheads calculated by a design model in the conceptual stage known as ASSET. Therefore, ISA is designed to support the naval architect in developing general arrangements, with the defined hull, decks, and bulkheads being necessary as inputs, a relatively high-detail starting point approach. The spaces arrangement is done in two steps. Firstly, spaces are allocated within a 'zone-deck', which is one deck within one vertical zone, illustrated in figure 6.3. Secondly, the assigned spaces are arranged in detail in each zone-deck. Priority is given first to the middle of the damage control deck. Priority at this stage is given to spaces depending on their area requirement, adjacency, separation, access, and shape features of the individual spaces [86].

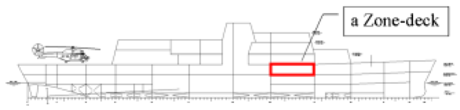


Figure 6.3: Definition of a zone-deck [86]

The ISA tool is found to be not applicable for a modelling layout method of the PPE generation tool as it is essential to have high-level geometrical details as inputs. The inputs that are necessary in ISA, are detailed geometrical constraints that are applicable for compartments arrangement and not for the PPE system building groups. During the initial phase of arranging a novel PPE system, the engine room is assumed to be a single compartment/room with unknown dimensions and therefore no geometrical constraints as the exact area needed is yet unknown and need to be determined.

6.1.4. WARGEAR

A new detailed ship layout plan tool used for surface warships during the early design stages known as WARship GEneral ARrangement (WARGEAR) was researched in 2022 by Joan le Poole [87]. This newly introduced arrangement tool is most comparable with ISA tool.

Currently, WARGEAR is used as support and as an add-on to low or medium level of detailed arrangement tool [87]. As an input to the WARGEAR tool a medium-detail of functional arrangement is needed. It was initially designed to be used complementary with the DMO FIDES tool that is based on the FBB approach. The WARGEAR tool incorporated a placement algorithm for staircases using probability and a network based approach together with a probabilistic selecting method to allocate spaces into compartments [87]. Additionally, cross-correlation technique to arrange spaces is used. This is a mathematical operation used in field like signal processing and is implemented for ship layout generation purposes for the first time. Finally, a ‘carving’-based approach is used for the connectivity purposes [87]. An example from WARGEAR tool, illustrating a generated layout of a specific deck is provided in figure 6.4.

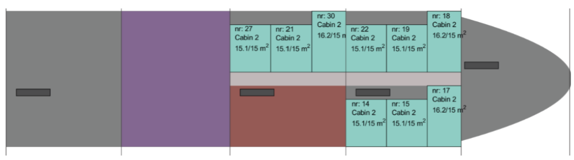


Figure 6.4: Example of WARGEAR generated layout [87]

6.1.5. Network Theory

A very different approach on ship layout design tools using network characteristics instead on focusing on volume or area was investigated by Gillespie [88] [89]. He was the first to investigate and analyze the relationships of ship compartments in a non-physical space using network connections. Networks have been proven to be useful with the allocation of spaces to compartments and can be powerful when dealing with a large number of system adjacency and global location requirements that need to be satisfied in a feasible layout [88].

Gillespie expressed that the human designers should be kept throughout the loop during the design process. Therefore, rather than just keeping the one best solution, a set of high-quality solutions are retained to be analyzed by human designers [89]. His network theory contradicted the FBB approach by Andrews [79] and the 3D packing approach by Van Oers [83], as he expressed that by gathering spaces or systems in to functional “blocks”, the positioning objects are reduced, leading to a much smaller combinational search space.

In his research a network partitioning method was used for the identification of compatible ship elements (i.e.,compartments, components,and/or systems) that could be located in the same structural zone. Gillespie used in his research network science that studies the properties such as interactions and relationships of items within a complex system. A network is made up of points known as *nodes* and they are connected by lines known as *edges* [90]. Networks can have several different characteristics, such as the edges can be directed or undirected, weighted or even signed. In ship design layouts each node can represent a compartment or space or even a specific component. Therefore, numerous information can be depicted from network graphs. This can be clearly shown from a simple network graph as illustrated in figure 6.5.

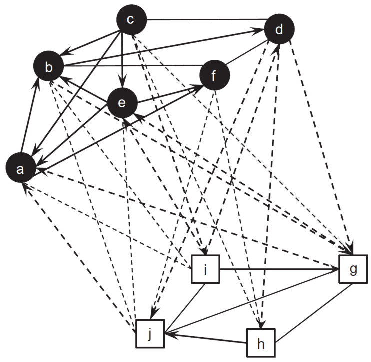


Figure 6.5: Network graph with positive intra-communitiy relationships (solid lines) and negative inter-community relationships(dashed lines) [88] [91]

6.1.6. Facility Layout Problem

The Facility Layout Problem (FLP) is a different modeling method which has been widely researched in various engineering domains over the past years [92]. This modeling approach is related with the arrangement of different facilities within a physical space and it has been mostly explored for industrial and manufacturing production systems where material handling costs are one of the greatest factors in the total operating expenses [93]. The design layout solutions obtained from the FLP modelling problems significantly impact the system performance later on and therefore play a vital role in the initial design [94]. More precisely, it has been investigated that the arrangement of facilities within a plant area has significant influence upon manufacturing costs, work in process, lead times and productivity [94]. Enormous improvements in overall efficiency and reduction of operational expenses up to 50% can be achieved when a good FLP is executed in a correct way [95].

According to Drira et al. (2007), a FLP is concerned with the facility arrangement within a physical space for the optimal production of any goods or provision of any services [94]. Additionally, a facility can be defined as a system that performs a specific job. Therefore, an FLP can be easily implemented as a modelling method for the engine room arrangement of a vessel, arranging facilities which in this case are represented by building groups (BGs) for the provision of a service which is represented by propulsion power. This was previously investigated by Roel van der Bles in 2019, who was the first to implement FLP for the ship engine room arrangement application [96].

The optimal arrangement configuration and the specific goal of an arrangement layout varies and must comply with the strategic initial objective(s) set by the specific organization. Examples can include the reduction of material handling costs, utilizing space more efficiently, minimizing the layout area, provide a safe and convenient environment etc. [97]. Even though FLP are highly important for the generation of optimal facility arrangements, they are far from being simple and easy to solve. The correct selection of the appropriate facility layout involves a complex and iterative process that depends on rating the entities that shape the system, identifying flows and important relationships between facilities [93]. Based on the computational complexity theory, FLPs are considered to be NP-complete (non-deterministic polynomial-time) optimization problems. This means that no solution algorithms exist that can deliver an optimum solution in a reasonable amount of time [98].

Despite their high degree of complexity, over the past years in literature several methods have been researched with these problems that can lead to satisfactory solutions within realistic amount of time.

Roel van der Bles in his Masters thesis used the FLP for the modelling of the machinery space on board vessels and more specifically on a trailing suction hopper dredger [96]. The developed tool has been found to provide useful insights during the conceptual design space of machinery space arrangement [96].

Consequently, from the literature investigation of the existing modelling solutions it has been concluded that specifically for the arrangement of PPE systems FLP is the most applicable method. This modelling approach has been widely applied for machinery application and has therefore been found the most appropriate for implementation for the layout generation of novel PPE systems. As FLPs have been widely researched for manufacturing applications, they can deal with the arrangement of BGs of different functions by capturing their unique requirements like clearance spaces for maintenance or Input/Output connection points and can handle the various BGs interconnections within the PPE system.

6.2. Resolution Approaches

6.2.1. Metaheuristics

Now that the modelling approach has been selected for the PPE system arrangement, investigation of the appropriate solution for solving the problem is carried out. The tree representation in figure 6.6 highlights the different FLP solution paths that can be followed [97], [94].

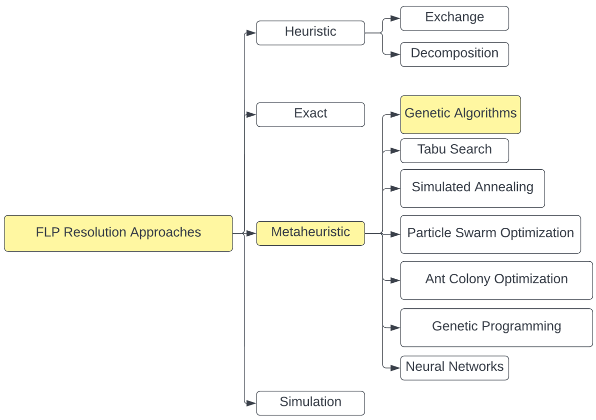


Figure 6.6: Resolution approaches for the Facility layout problem (FLP). Adapted from [96], [94], [97].

However, the different resolution approaches illustrated in figure 6.6, many of them are not well researched, they have few research work in the literature and many are not ideal to be used in FLP within a reasonable period of time, 6.7.

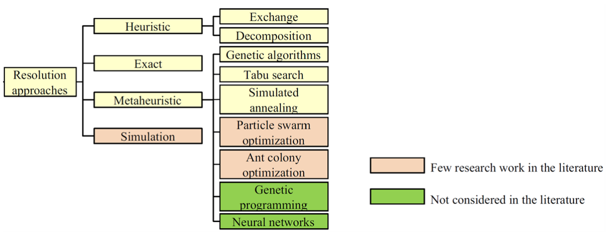


Figure 6.7: Resolution approaches for the Facility layout problem (FLP) [97].

A resolution approach that can examine the solution space quickly is essential. Heuristics approaches are most often problem-dependent approaches, defined for a given problem whereas, metaheuristics are problem-independent techniques that can be applied to a broad range of problems. Therefore, metaheuristics is one of the most suitable categories of resolution approaches that can be used.

In mathematical optimization, metaheuristics are higher level procedures designed to find adequately good solution in optimization problems with incomplete information or limited computational capacity [99], [100]. In simple words, they provide a subset of solutions by partially searching the search space which is otherwise too large to be completely explored [101]. Most metaheuristics have these properties [101]:

- Metaheuristics are strategies that guide the search process.
- The goal is to efficiently explore the search space in order to find near–optimal solutions.
- Techniques which constitute metaheuristic algorithms range from simple local search procedures to complex learning processes.
- Metaheuristic algorithms are approximate and usually non-deterministic.
- Metaheuristics are not problem-specific.

When investigating the resolution approaches it has been found that the Genetic Algorithm (GA) is widely used in optimisation problem and FLP due to its robustness [102]. Additionally, from a literature review undertaken it is observed that GA has been frequently used in the recent period as an optimization tool for FLP [102]. GA is ideal to be used as a global search algorithm and it can be easily implemented with other algorithms due to the algorithms' ability of handling constraints [103]. GA's ability of constraint handling by penalization as a property has made GA a preferred tool for multi-objective optimisation for FLP [104]. Generally, hybrid GA algorithm is chosen for the optimization of multiple objectives, such as material handling cost and space utilisation [104].

Therefore, Genetic Algorithm has been selected as the resolution approach together with the FLP in this thesis for the development of the PPE system design tool. Summarizing the key reasons for selecting Genetic Algorithm:

- Well established algorithm, extensively studied for FLP in literature.
- Generates layout solutions in a suitable time frame.
- Robust algorithm that can deal with errors.
- GA is ideal for global optimization problems.
- Can easily be implemented with other algorithms for local optimization.
- Can easily deal with multiple objective optimizations.
- Readily available on MATLAB for easy implementation.

Here it is important to note that the aim of this thesis report is to create a sufficient algorithm workflow that can create appropriate layouts for the PPE systems on board vessels and provide important ship design insights. The priority is not to create the most efficient and optimal algorithm as the report mainly focuses on the ship design aspect and the insights that can be generated from a developed design tool as an add-on to MBSE methodology and SPEC tool in the conceptual design stage. The focus of the report is not the computer science or purely mathematical aspect side.

The GA algorithm implemented as the resolution approach in the design tool will be directly obtained from MATLAB global optimization toolbox. Only the necessary tuning parameters that need to be adjusted, if found necessary will be varied. Additionally, the hybridization of GA algorithm with different solver algorithms from MATLAB's global optimization toolbox will be investigated. These solvers will be directly obtained from the provided MATLAB libraries.

6.2.2. Genetic Algorithm

In this section, a brief description on GA, the chosen resolution algorithm and its origins is provided.

GA comes from a wider class of optimization algorithms, known as Evolutionary Algorithms (EAs). This family of optimization algorithms is named in this way as the theories are formulated from various evolutionary concepts based on the environment to deal with different mathematical problems, mostly mathematical optimization problems.

More specifically, GA is a metaheuristic inspired by biologist Charles Darwin's theory of natural evolution. The algorithm is inspired from the environment and more specifically to imitate the natural selection process where survival of the fittest exist. The fittest individuals have a higher probability to survive and reproduce new offspring, passing on their inheritance and genes to the next generation.

In GA, a population of possible solutions, known as individuals evolve throughout the algorithm to achieve better solutions. Each individual, corresponding to a candidate solution has its own set of properties otherwise known as chromosomes. These properties are altered throughout the evolutionary algorithm process. In a high level description, GA starts with an initial population, which represents the first initial random generated solutions. This population goes through the algorithm loop, known as evolutionary loop until certain predefined criteria are met or a specified time is exceeded and the algorithm is then terminated.

7

PPE System General Arrangement Plan Tool's Methodology and Case Study

Now as the Facility Layout Problem and the (hybrid) Genetic Algorithm have been selected as the modelling and resolution approaches respectively, the model developed can now be discussed in detail. This chapter will address research sub-questions **2** and **3**.

The tool's methodology is developed on MATLAB and uses two additional MATLAB's official toolboxes, the Global Optimization and the Parallel Processing toolbox. In figure 7.1 the high level categories that will be discussed in this chapter of the report are shown. Firstly, the way the tool's optimization structure is formulated will be discussed. For instance, what inputs requirements are necessary and how they are imported, what are the defined optimization objectives and constraints. Additionally, more details on the optimization details on the hybrid GA algorithm and the visualizations will be provided. Finally, the specific case study ship with the specific PPE system that was selected will be presented.

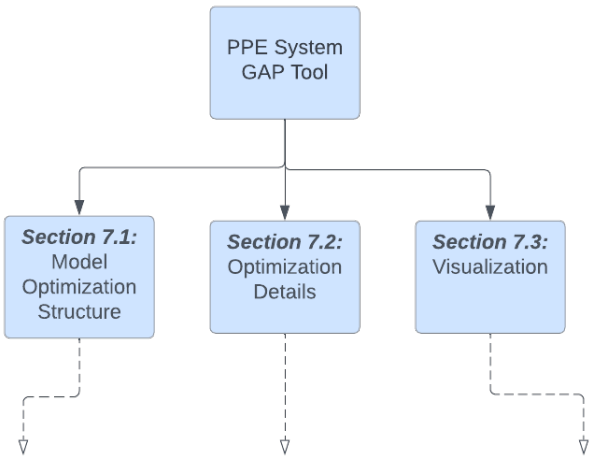


Figure 7.1: High Level Flow Diagram

7.1. Model Optimization Structure

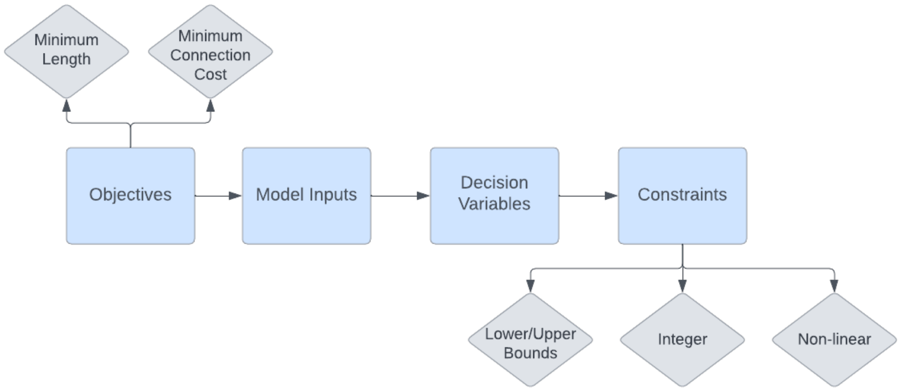


Figure 7.2: Model Optimization Structure Flow Diagram

7.1.1. Model Objectives

The PPE general arrangement tool aims to find the best layout solutions by performing a multi-objective optimization as it has been constructed upon two main objectives, otherwise known as objective functions.

First Objective - Minimization of Engine Room Length

The first objective aims to minimize the total area required for the engine envelope. On board vessels the area available is limited and all the PPE system Building Groups (BGs) within the engine room should be efficiently utilized.

A lot of ship use cases have existing compartment(s) with predetermined dimensions for the engine arrangement. Therefore, an important insight that the model will determine when applied, is whether the current compartment(s) has sufficient available area to accommodate the new determined novel PPE system or whether provision of additional space will be necessary.

Most use cases have fixed breadth and their engine room most commonly transversely extends across the whole vessel's breadth, it has been decided to keep the width of the engine envelope fixed throughout the optimization. Thus, the area minimization will be achieved by varying length only. In other words, the first objective aims to find general arrangement layout solutions with the shortest possible overall length.

The tool throughout the optimization is updated about the BGs positions and the location of the rightmost BG together with its required (right) clearance space determines the maximum length. The tool updates the total engine room length and tries to minimize it as much as possible. A small-scale test with five BGs as illustrated in figure 7.3, indicates that the engine envelope's length has been optimized at $9.9m$ and determined by the rightmost BG and more specifically by its right clearance distance. Simultaneously, the engine envelope's width is remaining fixed, as specified at ($10m$).

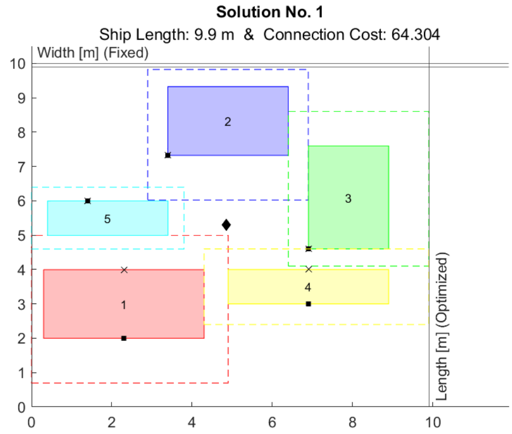


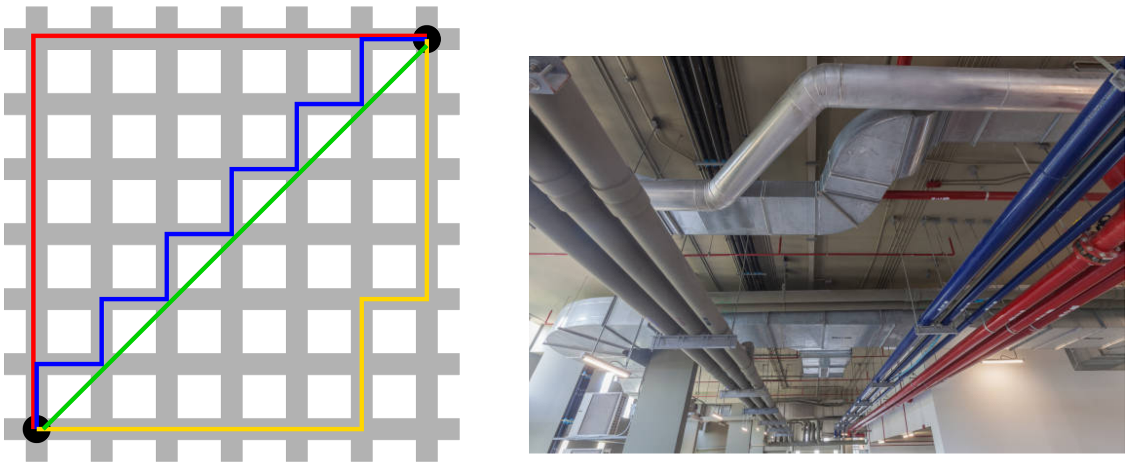
Figure 7.3: An example layout from the general arrangement tool indicating the minimization of length determined by the green and yellow BGs at $(9.9m)$

Second Objective - Minimization of Total Connection Cost

A main reason for using the Facility Layout Problem as the modelling method, is the ability to capture the different types of connections between the BGs. The second objective seeks the minimization of the connection cost between the BGs. The total connection cost is the total sum of the product of the individual connection distance between two components and a factor (CM), which is used to describe the connection. The objectives function formulation used in the optimization is given by Drira et al. [94] and also implemented by Roel van der Bles [96]:

$$\sum_{i=1}^{N}\sum_{j=1}^{N} CM_{ij} \cdot d_{ij} = CM_{ij} \cdot (\mid x_{i_{out}} - x_{j_{in}} \mid + \mid y_{i_{out}} - y_{j_{in}} \mid)$$

d_{ij} is the distance between the output of component i and the input of component j in rectilinear form. Manhattan distance was selected over Euclidean distance in order for the model to represent more realistic and ideally designed conditions, as seen in 7.4b. On board vessels all connections such as pipes and cables must be designed and sorted in neat and well-order manner to enable the proper maintenance and inspections throughout the vessel's lifetime. Figure 7.4a illustrates the difference between Manhattan distancing represented by the yellow, blue and red line and the Euclidean distancing represented by the green line.



(a) Figure illustrating Manhattan versus Euclidean distance. The red, blue, and yellow lines all have the same length (12), whereas the green line has length $\sqrt{72} \approx 8.5$ [105]. Adopted from [96].

(b) Connections on board vessels

Figure 7.4: Connection distance calculation between building groups.

CM_{ij} is a factor between the output of component i and the input of component j that can be used in various ways. It can be used as a relative weight factor that indicates the connection importance based on its physical type or based on the rationale inputted by the ship designers. For instance, when focusing on the physical connection type perspective, mechanical transmission can be considered a highly important connection that must therefore be limited within the engine room. On the other hand, some BGs do no have an actual physical connection but need to located nearby for maintenance purposes. These relationships require the rationale of ship designers. Another major drive that can influence the general arrangement of a PPE system is the actual price cost of connections. In this model these relations are implemented using a symmetrical connection matrix which can be used for both qualifying and quantifying relationships of BGs in the PPE system layout design. This connection matrix includes all the defined CM_{ij} values shown in the equation for all the interconnections between all the BGs. An example of a relationship matrix can be seen in figure 8.7, which shows the connection matrix defined for the components that serve as input in the testings performed in chapter 8.

7.1.2. Model Inputs

In the following section the way the optimization tool was defined and the specific way the it handles all the input parameters will be explained. The model inputs for modelling the problem as a facility layout problem and the choices made for this report are originated from Ahmadi et al. research paper about the multiple-floor facility layout problem and have been adapted by Roel van der Bles in his master thesis [97], [96].

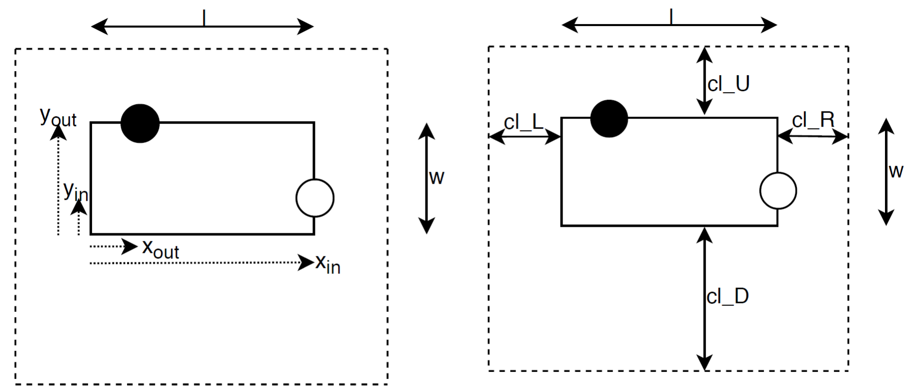
Firstly, is important to address that the design tool was developed to directly read all input data and variables needed for a specific PPE system from an excel spreadsheet file. The easy implementation of different use cases and different PPE systems was considered a highly useful feature and it was stated in section 5.1.2 as an initial tool requirement. The design tool offers the ability to test different use cases PPE systems with no adjustments on the tool code. By just adjusting an excel spreadsheet file, different vessels' PPE systems layouts can be generated. Therefore, adjustments and alterations on the actual code of the tool that can delay future tests and complicate the procedure are not required. These input parameters obtained from the excel file consist of:

Components/Colors/Code: All BGs that make up the PPE system, are directly obtained from the excel file including the names, a unique color and code used to represent them on the final layouts generated.

Dimensions: All BGs are assumed to have a regular rectangular shape. Therefore, individual dimensions for each building block's length and width in meters are predetermined in the excel file.

Margins: The BGs except for their predetermined dimensions, they require a certain clearance space or margin around them for different purposes. Reasons that make margins around BGs necessary can include; maintenance access, safety laws, space for routes to move around, safe operation etc. These margins in most FLP are uniformly modelled with equal dimensions around each facility for simplification. In other words, for a specific rectangular facility a clearance of one meter in all four sides is assigned. However, in order to obtain more realistic layouts and represent more lifelike conditions, these margins were implemented within the tool with the ability to be separately defined for each side. In real practical conditions a specific building block may have a clearance requirement only on one specific side and all the sides can be have the ability to be arranged near the wall or other BGs. For instance, the batteries can be of a modular design in the derived PPE system that require most clearance in the face side of the BG. However, on the side no margin can be required and the batteries can be positioned next to each other without any in between clearance space. Moreover, it is important to clarify that the clearance spaces are modelled in a way where they can overlap with each other but not the actual building groups themselves. This can be clearly seen from figure 7.3.

Input/Output (I/O) locations: Each BG can be modelled with one input and one output location point. These input and output location points are defined from the bottom left corner of each component in horizontal and vertical distance. However, even if a BG has more than one input and/or outputs, the model can handle them but assumes that their exit/entrance point start from the defined inputs and output location. It is assumed that all defined connections for each facility exit/enter from the specified I/O point defined.



(a) Length, width, and in- and output locations of a component

(b) Clearances around the component are defined up, down, left and right of the component

Figure 7.5: BGs dimensions, unequal margins and I/O locations [96].

Rotations: When looking for the optimal layout within the engine room it was essential to make sure that the BG could rotate as they have unequal rectangular shapes with different defined margins around them. In this way, multiple layouts with different BG orientation can be evaluated. The tool developed has the ability to rotationally constraint BGs if needed. For instance, BGs that are necessary not to rotate throughout the optimization can include the mechanical transmission and the main dual-fuel engines as they should always be in a longitudinal orientation within the engine room. The current model can handle only 0 and 90 degree rotation, with the rotation of the BGs being counterclockwise. This poses a limitation in terms of the connection distance calculated between BGs. However, this limitation is minimal as the connection distance is only affected from the relative position of input and output positions of BGs. Therefore, it only has a minor effect since the distance between two BGs is mostly determined by the actual BGs locations. The ship designers and marine engineers can always careful revise the generated layouts obtained the optimization tool and simply decide to rotate 180 degrees few components if found useful.

Positional Constraints: Furthermore, the tool has the ability to constraint BGs, partially or fully in specific positions within the engine room. In the excel file a X_{min} and a X_{max} value can set a minimum and a maximum positional constraint, respectively on a BG along the length of the ship. For instance, if X_{min} and X_{max} are set at the same value for a BG, then the x-coordinate is fully restricted and is set at a specific engine room length position throughout the optimization. In the same way a Y_{min} and Y_{max} can restrict a facility in the vertical direction which is the width of the vessel. The restrictive positional coordinates (X_{min}, X_{max}, Y_{min}, Y_{max}) are measured from the bottom left corner of the engine room with the corresponding $(0, 0)$ coordinates until the bottom left corner of a BG.

Weight: Additionally, the weight in kilograms for each facility is determined, as the Centre of Gravity (CoG) is generated from the tool. The CoG is an important parameter to be included in the results, as it is an important insight for ship designers. The weight of each rectangular BG has been assumed to act at its geometrical center.

Connection Matrix: The PPE consists of many different buildings groups, each responsible for different functions. However, when designing the PPE system's layout these BGs cannot be taken in consideration in isolation. Many different types of interaction exist. A defined connection matrix needs to be provided to enable the tool to optimize the PPE system layout upon these highly influential BGs relationships.

Ship Width: As already discussed, the fixed width dimension in meters of the engine room that is kept fixed throughout the optimization and all BGs should not exceed, needs to be provided in the excel file.

7.1.3. Decision Variables

In this section of the report the way the decision variable notation of the design tool is explained. The specific notation was adapted from Roel van der Bles master thesis [96]. The variable notation implemented by Roel was developed and provided by Yarpiz, where he implemented the Facility Layout Design using Particle Swarm Optimization(PSO) in MATLAB [106]. This implementation provided by Yarpiz, is aimed to be a resource of academic and professional scientific source codes and tutorials [106].

To understand how the decision variables are defined within the optimization tool is essential to understand some important optimization definitions and formulations. The FLP implemented as the optimization's modelling method is an optimization problem which according to Rao is formulated in the following way [107], [96]:

$$\text{Find } X = \{x_1 ... x_n\} \text{ which minimizes } f(X)$$

subject to constraints:

$$g_j(X) \leq 0, j = 1, 2..., m$$

$$l_j(X) = 0, j = 1, 2..., p$$

When looking into the design of any engineering system from a mathematical perspective it can be formulated by a set of quantities. Some of these quantities are determined in advance and are known as preassigned parameters [107]. In the developed optimization tool examples of preassigned parameters can be considered the fixed ship's engine room width or the BGs dimensions that are considered fixed. All the other quantities are treated as decision or design variables and they are represented collectively by a design vector, $X = \{x_1, x_2, ..., x_n\}$ [107]. $g_i(X)$ and $l_j(X)$ represent the inequality and equality constraints of the problem respectively. The design vector X contains all the variables of the problem [107].

In the equation shown above X represents the design vector with n variables and $f(X)$ is the objective function that should be minimized. As discussed previously, the developed tool aims to find solutions by minimizing two main objective functions, the engine room's length and the total connection cost. Therefore, as the optimization problem consists of multiple objectives functions the formula is rewritten in the following way:

$$\text{Find } X = \{x_1 ... x_n\} \text{ which minimizes } \sum_{i=1}^{k} f(X)$$

The layout of the PPE system is determined by the variable positions of the BGs. Each BG has three corresponding decision variables that define its location and rotation in the engine room. Those are its x and y-coordinates and the r variable that controls the 90 degree rotation. Therefore the formulated design vector for the problem with n defined BGs is:

$$X = \{x_1 \ldots x_n, y_1 \ldots y_n, r_1 \ldots r_n\}$$

Where for each BG a x-coordinate, a y-coordinate and a rotation is defined. Three properties correspond to each BG the optimization problem has $3n$ dimensions.

7.1.4. Optimization Constraints

After identifying and constructing the decision variables which are the values of interest, the logical conditions of the optimization problem needed to be defined. These are known as the optimization constraints. Constraints are the restrictions on the decision variables that limit the value the decision variables can take.

In any FLP, numerous constraints need to be properly defined to achieve feasible layouts, where the physical placement of components are not violated. For instance, no two facilities can occupy the same physical space and all facilities should be arranged within the defined engine space.

Lower and Upper Bounds: Lower and Upper Bounds are the most simple version of constraints. These are absolute limits applied on the range of values the decision variables can obtain. After defining the structure of the decision variables it was essential to define both the lower and upper bounds for each component's x-position, y-position and rotation. In other words, the upper and lower bounds define the maximum and minimum positional and rotational values respectively a building block can take.

The lower and upper bounds, both for the x-position(along the ship's length) and y-position (along the ship's width) of the facility the margins needed to be facilitated within the engine envelop. The lower and upper bounds for the rotational ability of a component were defined in an integer form. For instance, for a component that could rotate 0 is defined as the lower bound and 1 as the upper bound.

Integer Constraints: Integer constraints are used to restrict some or all of the variables to take on only integer values. Integer constraints have been used in the optimization tool to handle the rotational ability of BGs. The third coordinate of each BG, that controls the rotation (r), can either take a value of 0 or 1. When 1 is initially defined in the excel file for a specific BG, the BG is able to freely rotate between 0 or 90 degrees during the optimization. When r for a specific BG is set at 0, the BG cannot rotate and remains fixed throughout the optimization process.

Nonlinear Constraints: Nonlinear constraints allow you to restrict the solution to any region that can be described in terms of smooth functions. In the FLP optimization tool 2 specific non-linear constraints were implemented. The first non-linear constraint needed to ensure that all components and their margins did not exceed the maximum room's width. The second non-linear constraint implemented was to ensure no overlap between the BGs. This was defined in a way that the margins of different components can overlap but not the actual BGs.

7.2. Optimization Details

In this part the way the developed hybrid GA algorithm works will be elaborated.

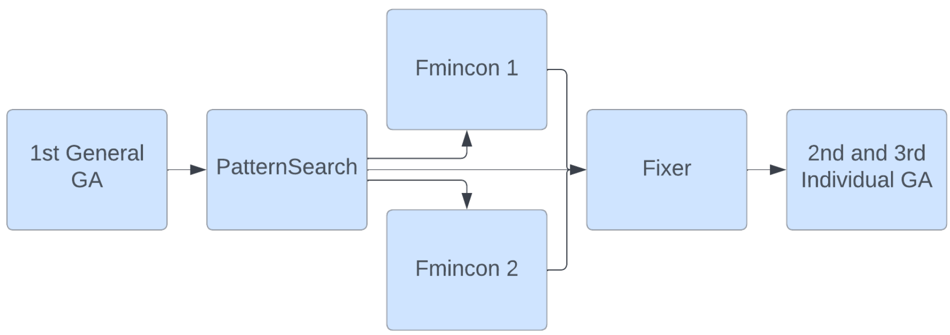


Figure 7.6: Optimization Details Flow Diagram

7.2.1. First General Genetic Algorithm

The first section of the optimization algorithm process starts with a controlled, elitist genetic algorithm (Non dominated Sorting Genetic Algorithm-II) [108]. The NSGA-II algorithm is obtained from MATLAB's Global Optimization Toolbox. An elitist GA always favors individuals with better fitness value (rank). A controlled elitist GA also favors individuals that can help increase the diversity of the population even if they have a lower fitness value. It is important to maintain the diversity of population for convergence to an optimal Pareto front. Diversity is maintained by controlling the elite members of the population as the algorithm progresses.

GA starts with random layouts. It avoids all constraints by default. It creates random layouts, checks for constraints, observe that some rectangles intersect, discard that layout and create a new random one until all constraints are satisfied. This leads to layouts that have a lot of spacing between them. It makes the layouts better with each iteration (population) but it is a slow improvement.

7.2.2. PatternSearch

The GA used in the first step finds feasible solutions but as explained before and seen from literature, the algorithm is ideal from global and not local optimization. In the next step of the hybrid algorithm the feasible solutions obtained from the first GA proceed to be optimized by PatternSearch Solver. PatternSearch is an algorithm from the global optimization toolbox, ideal for local optimization and could be easily implemented on the first GA and the tool [109].

PatternSearch is a direct algorithm that can handle bounds and non-linear constraints. This was necessary, as our optimization algorithm structure includes non-linear constraints.The pattern search algorithm uses the Augmented Lagrangian Pattern Search (ALPS) algorithm to solve nonlinear constraint problems [110]. For more details on the mathematics used refer to the technical report by Kolda [111]. Direct algorithms are efficient and can be used to solve non-smooth optimization problems [112]. Non-smooth functions include non-differentiable and discontinuous functions and this is the case with the complex FLP defined in our tool. Therefore, this algorithm is used as the defined objective functions and constraints did not need to be differentiable or continuous [112]. PatternSearch is advised to be used for non-smooth problems.

PatternSearch algorithm starts from a provided initial point, the first GA's solutions and sequentially converges to a more optimal point. The objective function value of the provided points (layouts) in the sequence can only decrease or remain the same in each iteration. PatternSearch iteratively searches on the Pareto front of the first GA's layouts looking for further improved and non-dominated points [113], [114].

PatternSearch cannot handle integer constraints. As seen in the previous section 7.1.4, integer constraints are implemented and used to handle the rotational ability of the building groups. Therefore, for PatternSearch the rotations are not altered and remain unchanged. The algorithm tries to find better solutions by only moving the the BGs position.

Each new solver in the design tool starts working on the solutions from the previous solver. PatternSearch tries to find more optimal solutions on multiple objectives and is therefore possible that it can find different improvements for the two different objectives. Since dealing with multiple objectives, one solution can produce more than one solutions when further optimized. Therefore, the number of solutions exiting from PatternSearch can be more than from the first GA.

7.2.3. Fmincon 1 and 2

The next part of the hybrid algorithm implements Fmincon which is another MATLAB solver that tries to find minimum of constrained nonlinear multi-variable functions. Fmincon uses a sequential quadratic programming (SQP) method. In this method, the function solves a quadratic programming (QP) subproblem at each iteration. For more details on the mathematical details refer to Chapter 18 of Nocedal and Wright [115], [116]. Fmincon does not support multiple objectives, so the model structure has been adjusted in this part to run twice with one objective at a time. The first fmincon optimizes for minimum length and the second for minimum connection cost.

7.2.4. Fixer

As mentioned earlier, the first GA does not ideally optimize the layouts and therefore PatternSearch and fmincon have been applied. In this part of the algorithm a fixer code has been created to ensure that there is no unitized space in the engine room. The fixer code moves all BGs to the left starting from the leftmost component. This ensures the utilization of space, minimizing the engine room as much as possible.

The initial PPE layouts used in the fixer are both from patternsearch and from the fmincons. This was added to ensure that if the fmincons generated an error the algorithm could proceed with the patternseatch optimized layouts. Furthermore, a function was developed in the design tool to ensure that at the end of every solver very similar solutions that are within a tolerance are discarded.

7.2.5. Second and Third Individual Genetic Algorithm

The final step in the hybrid algorithm implements Deb's NSGA-II once again [108]. In this step the code freezes all BGs except one at a time and optimizes by modifying the position of only one BG. This is repeated twice with the 2nd individual GA starting from the rightmost BG until the leftmost and the 3rd individual GA starts in the opposite direction from the leftmost BG. In other words, in the final two GAs, each BG is optimized separately two times, once with the second and once with the third GA. For instance, if a PPE system consists of 20 BGs, GA runs 40 times.

7.3. Tool Visualizations

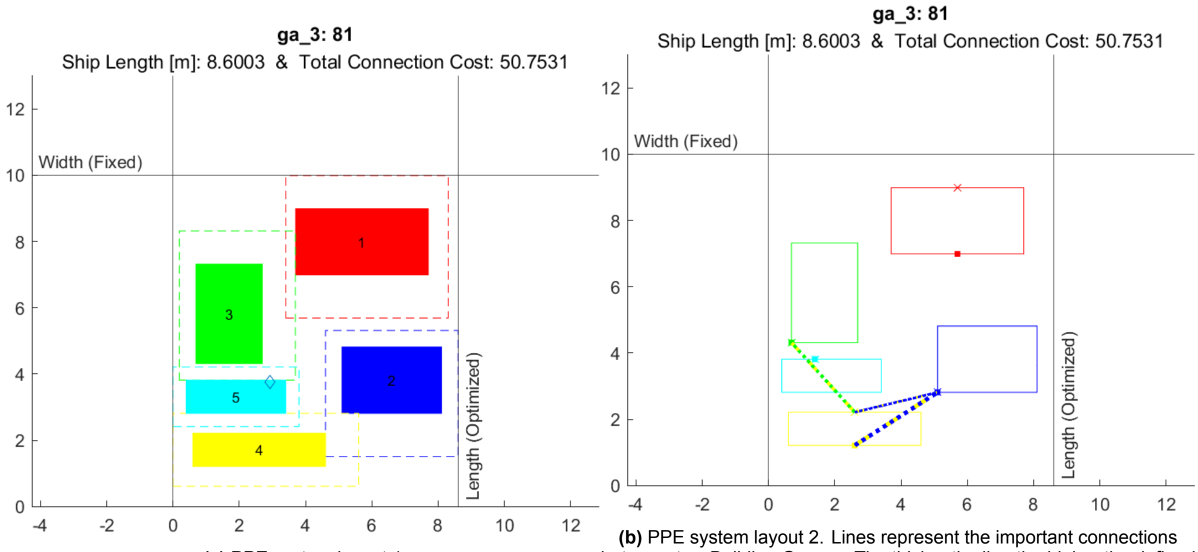
In this section of the report the way in which the generated results are visualized are illustrated. The visualization results presented are based on a small-scale test with 5 facilities. As mentioned in section 5.1.2, the proper visualization presentation was defined as an essential requirement. Furthermore, with the illustration of an example, the design tool response and results are investigated for the first time on a small-scale. The example is constructed in the same way like an actual PPE system and the same level of input complexity is necessary. The required input implemented for the example test can be seen in appendix A.

7.3.1. Generated Layouts

The design tool generates few different variations of layout plots. As seen in figure 7.7, two different layouts are presented side to side. More specifically, in sub-figure 7.7a, the facilities are presented with their corresponding surrounding clearance space and the exact CoG coordinate is illustrated in a blue diamond shape. In sub-figure 7.7b, visualization emphasis is given on the input and output position of the facilities which are represented with a dot-mark and an x-mark respectively and the most important connections are presented.

In the small scale example performed the CM_{ij} weight values assigned to qualify the different connections range from 1 to 5.The connection matrix used can be seen in appendix A. In section 8.3.2, more details will be provided on how the tool differentiates the different connection types and their importance. In layout in sub-figure 7.7b only the connections with $CM_{ij} \geq 3$ are presented. This specific visualization setting can be altered within the tool, where none or even all connections can be presented if preferred. It can be clearly seen from 7.7b, that in this specific layout the design tool successfully positioned the facilities in order for the most important connections to be nearby, minimizing their distance and consequently the total connection cost.

The connection lines are multi-coloured, formed with the two colours of the corresponding facilities and the thickness illustrates the connection importance. For instance, the thickest connection between the blue facility's output point and the yellow facility's input point is the thickest connection and therefore the most important. Additionally, the required input specifics used for the example test are provided in Appendix A. It is important to note here that even that the connection lines are visualized in Euclidean distance the connection lines between the different facilities are calculated in Manhattan distance, as explained in section 7.1.1.



(a) PPE system layout 1

(b) PPE system layout 2. Lines represent the important connections between two Building Groups. The thicker the line the higher the defined connection importance.

Figure 7.7: PPE generated layouts 1 and 2

In figure 7.8 a combined layout generated by the tool, illustrating all information is presented. Moreover, as shown in figure 7.9, the designers have the ability to select which connections will be presented on the arrangement layouts. In figure 7.9a only connections with $CM_{ij} \geq 3$ are presented, whereas in figure 7.9b all connections are shown.

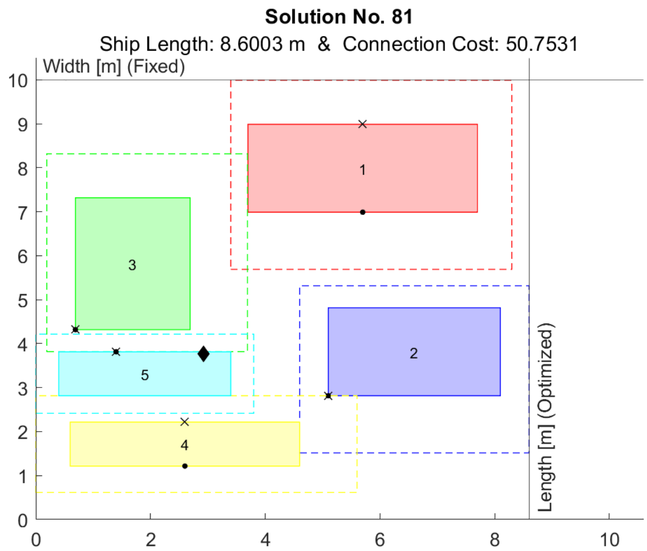
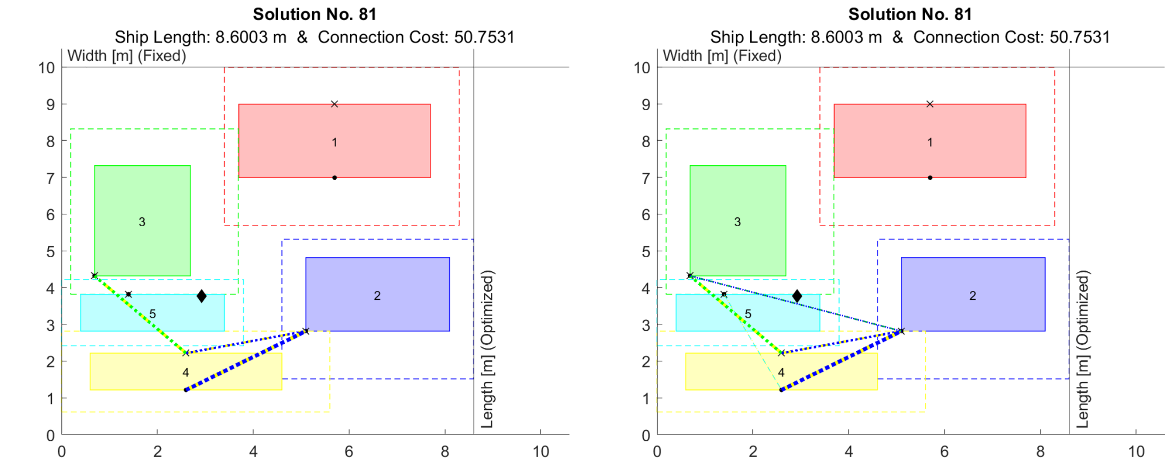


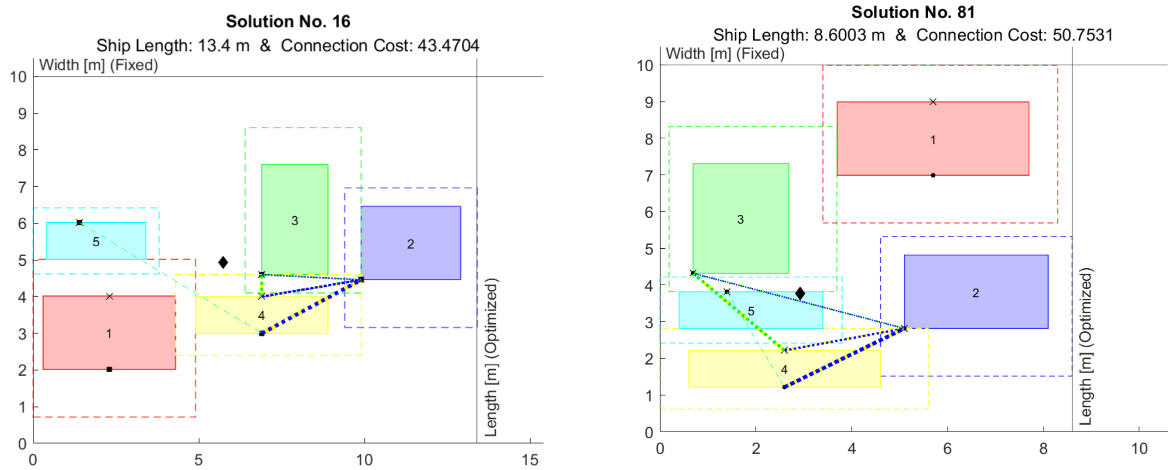
Figure 7.8: PPE system layout



(a) PPE system layout with connections of $CM_{ij} \geq 3$ **(b)** PPE system layout with all CM_{ij} weight values connections

Figure 7.9: PPE generated layouts 4 and 5

Figure 7.10 presents two different layouts generated from the design tool example test for comparison. In sub-figure 7.10a, the connection cost is further decreased at the expense of a higher engine room's length. Whereas in sub-figure 7.10b a higher connection cost arrangement with lower overall length is present. In Appendix A more generated example layouts are presented. As stated in section 5.1.2, an essential tool requirement was the generation of various alternative arrangement layouts for the appropriate trade-off analysis.



(a) Example layout with the best total connection cost **(b)** Example layout with the best length

Figure 7.10: PPE generated layouts 4 and 5

7.3.2. Additional Features

The design tool generates some additional important figures. Firstly, a pareto figure is created with all the generated layouts showing all the different solvers contribution against the two objectives, as seen in figure 8.13. This figure can illustrate how the algorithm process optimized the solutions and how each individual solver contributed to the optimization.

Additionally, a table with the step-wise improvements of the 2 objective functions mean values and the generated number of PPE system layouts is generated. See table in Appendix B.2. For each layout a table presenting the the exact details for each BG position coordinates, the engine room length, the total connection cost and the exact CoG coordinates can be generated. This is illustrated in an example table presented in Appendix B.4.

Finally, the design tool has been developed to save all different solver steps in different files within a new test folder. Within the file for each solver, the exact workspace environment and the layouts of that step are saved. A folder named "results", stores all the different test folders, named after the date and time of their execution. This enables the detailed investigation and analysis of all the layouts and the design tools specifics.

7.4. Power, Propulsion and Energy system Case Study

This section investigates research sub-question **3**. In order to test the capabilities of the developed design tool for the initial generation of PPE systems arrangements during the conceptual design stage, a specific case study ship with a specific PPE system was selected. The future power, propulsion and energy (PPE) systems of a large motor yacht, conceptually designed in the physical architecture of Capella was chosen.

7.4.1. Solution Exploration

As previously mentioned, the adoption of MBSE application within MARIN aids in the design procedures from the initial stages and mitigates the risks of future-proof bunker and new machinery spaces solutions. The design tool for the generation of arrangement layouts of the novel PPE system within the machinery space will work complementary with the developed MBSE physical architecture and the SPEC analysis. This will enable the visualisation and further enhance the juvenile developed PPE solutions, originated from various analyses and discussions, all captured within the MBSE environment.

During the conceptual design, the MBSE physical architecture of the large motor yacht PPE system was developed by MARIN which consists of various crucial building groups. The MBSE physical architecture can include a massive amount of details and information for each building group and all physical connections. Prior to that, the exploration phase where the needs analysis and the SPEC analysis are conducted based on the appropriate reference ships. For the large motor yacht the typical specifications used from the reference ships are revealed below in Table 7.1. The specific objective of the large motor yacht is: *'Start with the typical operational specifications as they are now and try to implement a partial zero emissions solution.'*

Table 7.1: Typical operational specifications for the reference ship for use case 10 [28].

Autonomous range [naut. miles]	Max speed – fully loaded [kts]	Displacement – fully loaded [metric tonnes]	DWT [metric tonnes]	Gross tonnage [GT]	Installed power prime movers [kW]	Engine room architecture	Mission type with highest effective energy	Effective energy
3500	16.5	920	180	970	2800	ICE-direct	Type III – Atlantic crossing	330

When compared to the the reference vessel used in SPEC analysis, the autonomous range was decided to be reduced from 3500NMi to 2700NMi, which is the bare minimum to satisfy mission type **III** Atlantic crossing, this is illustrated in Table 7.2 [28]. At the start of the project, both hull and superstructure are assumed to remain unaltered as the reference ship [28]. The large motor yacht, is a vessel designed for leisure and to have the ability to sail both in deep and coastal seas and must be cable to transport the crew and passengers. This main capability can be subdivided into three categories: to provide propulsion, be able to perform all auxiliary services including leisure services and to carry out emergency services [28].

Before reaching the physical architecture, both the operational and system architecture of the yacht's PPE system have been defined including the consumer power time characteristics (PTCs). These are important graphs that can illustrate the characteristics of the power consumption over time of the vessel's propulsion and auxiliary consumers [28]. The system architecture is important for defining the boundaries of the defined PPE system and understand what actors (eg captain or crew) or systems (eg auxiliary services) outside the boundary of the PPE system are required. For instance, the leisure and payload services that are a sub-category to the auxiliary services have been decided to be outside the scope and the boundaries of the PPE system. The PPE system is just responsible to distribute the required leisure and payload services power and that is where the boundaries have been set. The system architecture is illustrated in figure 7.11.

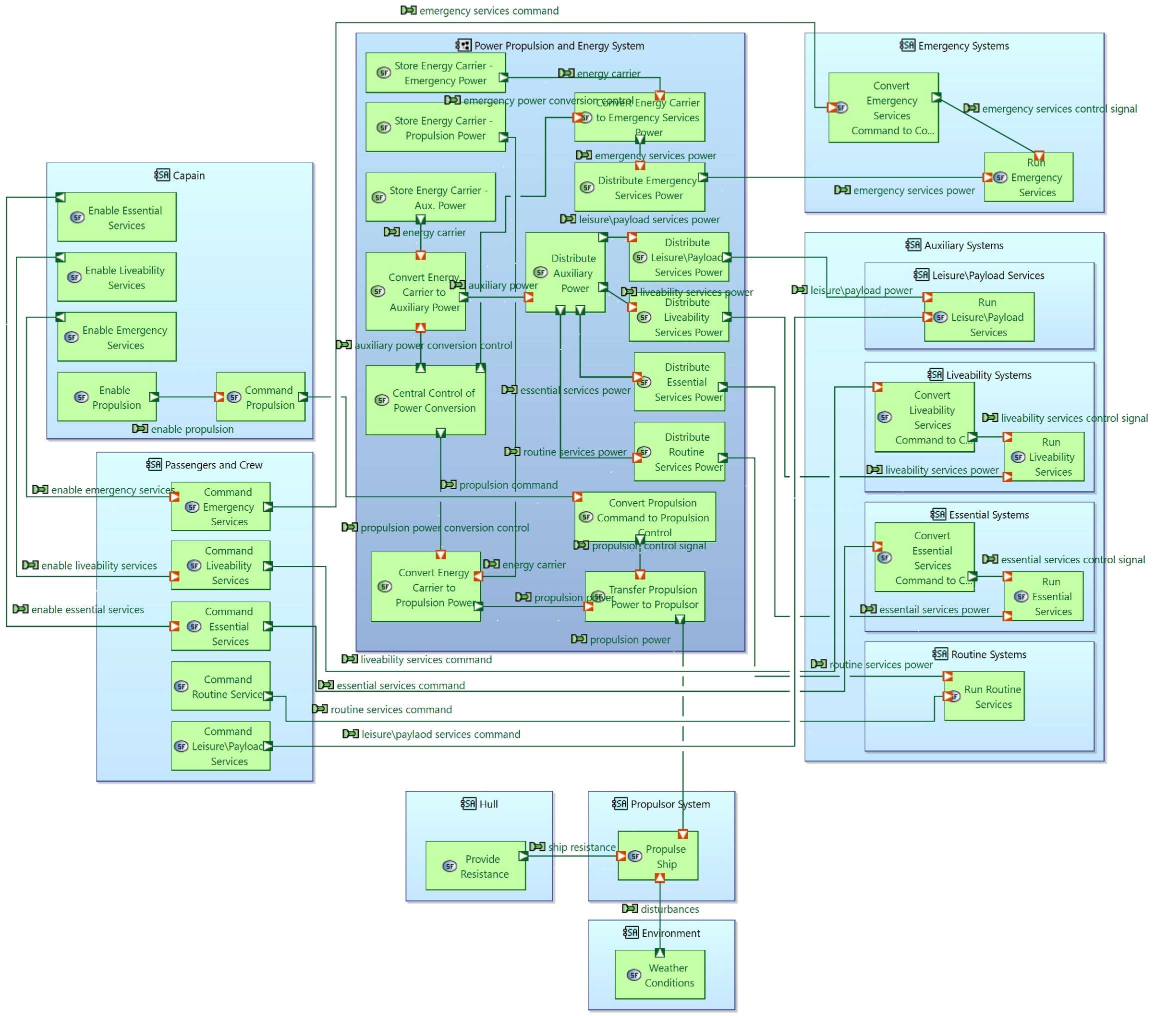


Figure 7.11: MBSE large motor yacht's System Architecture

Additionally, as previously mentioned other essential graphs and tables that capture the Power Time Characteristics (PTCs) of the PPE system are linked to the MBSE system architecture. These capture the important system requirements to the power exchanges [28]. These are namely known as MPTCs, EPDTs, and EPTCs [28]:

- *Mission power time charts (MPTCs)* are charts that show the specifically for mission types the consumed power in time.
- *Event power distribution tables (EPDTs)* are tables that show specifically for mission types the event occurrence distribution with the needed power properties.
- *Event power time charts (EPTCs)* are used for analysing event data with focus on dynamics. EPTCs cover an event and have a time step of approximately one second.

Table 7.2: Results of the power time analysis (MPTC) of large motor yacht [28].

Mission type	Effective energy		Emissions requirements	
	Criterion	Effective energy [MWh]	GHG	Pollutants
I – Busy leisure voyage	Endurance: 14 Days	139	50% CN	Tier III
II – Zero emission leisure	Endurance: 34 Hrs	5	50% CN	ZE
III – Atlantic crossing	Autonomy: 2700 Nmi	255	None	IMO Tier II

Table 7.3: Event power distribution table (EPDT) mission type II of large motor yacht [28].

Events	Speed [Kts]	P_{prop} [kW]	$P_{payload}$ [kW]	P_{Aux} [kW]	P_{Tot} [kW]	Distribution [#]	Distribution [%]
Anchoring	2	4	0	154	158	3	9
At anchor	0	0	0	121	121	25	74
Berthed	0	0	0	114	114	0	0
Berthing	0	218,5	0	176	395	0	0
De-anchoring	2	4	0	198	202	3	9
Economic cruising	11	673,3	0	132	805	0	0
Economic cruising in sea state 3	11	774,3	0	154	928	0	0
Economic cruising in sea state 6	11	908,9	0	154	1063	0	0
Fast cruising	14	1388	0	132	1520	0	0
Fast cruising in sea state 3	13,4	1399,7	0	154	1554	0	0
Fast cruising in sea state 6	12,7	1398,8	0	154	1553	0	0
Manoeuvring	0	207	0	176	383	1	3
Max speed	16,5	2272,3	0	132	2404	0	0
Slow sailing	7,5	213,4	0	132	345	1	3
Station keeping	0	345	0	220	565	0	0
Unberthing	0	218,5	0	176	395	0	0
Very slow sailing	4	32,4	0	132	164	1	3

7.4.2. PPE System Description

Use Cases, are vessels with existing PPE systems that do not contribute in emissions reduction and have predefined technical compartment dimensions. The general arrangement of these vessels are not necessarily suited for novel PPE systems and the investigation of adopting alternative PPE systems that minimize emissions within the given dimensions is necessary specifically for each Use Case.

Use Case - Large Motor Yacht

In this section the PPE system of the large motor yacht Use Case is the main focus. It has been explained in detail how the SPEC tool and the MBSE operational, system and physical architecture are utilized and developed throughout the design process. The developed PPE system should now be appropriately modelled by capturing all building groups (BGs) and their important parameters, aiding in the generation of the proper arrangement layouts.

The novel PPE system that is aimed to be implemented on the large motor yacht and reduced emissions is a Dual Fuel (DF) Methanol Internal Combustion Engine (ICE) with Methanol-Hydrogen Fuel Cells. The detailed building group list and a schematic diagram of the PPE system is provided in Table 7.4 and 7.12 respectively.

Table 7.4: PPE building groups of Use Case 10 obtained from the MBSE physical architecture

Layout ID	Building Group Name	Layout ID	Building Group Name
1	Methanol Fuel Preparation	14	AC Distribution
2	Diesel Day Supply	15	Lithium-ion Battery (1)
3	Hydrogen Supply	16	Lithium-ion Battery (2)
4	(PEM) Fuel Cell (1)	17	Nitrogen Tank
5	(PEM) Fuel Cell (2)	18	Mechanical Transmission (1)
6	Methanol DF Main Engine (1)	19	Mechanical Transmission (2)
7	Methanol DF Main Engine (2)	20	Methanol Reformer (1)
8	ESM Converter (1)	21	Methanol Reformer (2)
9	ESM Converter (2)	22	Methanol Reformer (3)
10	ESM Machine (1)	23	Methanol Reformer (4)
11	ESM Machine (2)	24	Central Cooling Water
12	DC Distribution (1)	25	Fresh Water Tank
13	DC Distribution (2)		

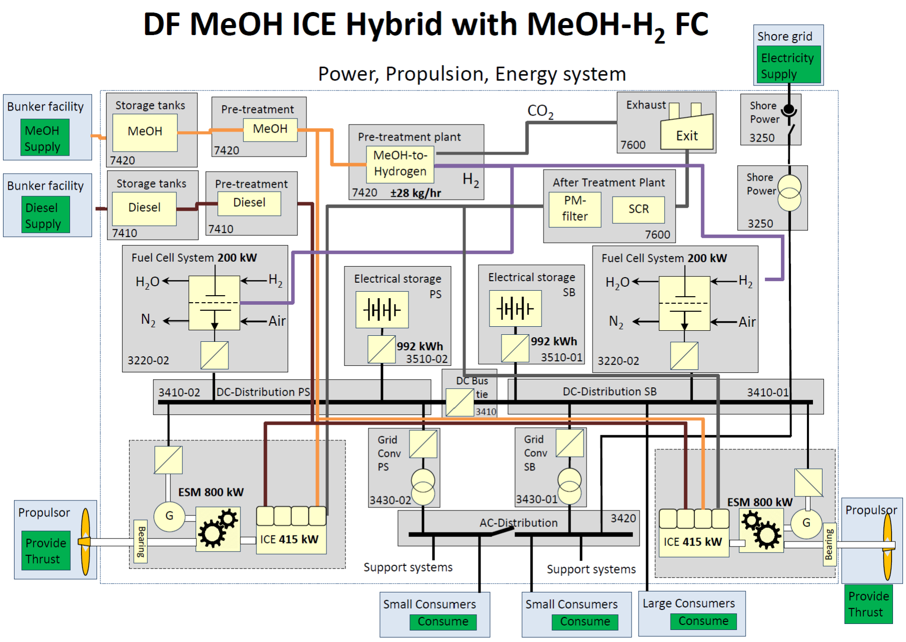


Figure 7.12: PPE Schematic Diagram

The PPE system consists of 2 *Dual Fuel Main Engines* running on Methanol and/or Diesel. *Diesel Day Supply BG* performs the day-tank functions as the immediate fuel source, receiving fuel from a larger fuel storage tank. The larger diesel fuel storage, Diesel Supply BG was not included for the general arrangement tool. It has been decided after discussions that these diesel storage unit should be excluded from the engine room layout modelling as they it generally suited around the vessel in various tanks to distribute the weight and volume. The *Methanol Fuel Preparation BG* is responsible for preparing the fuel which can be either Methanol or Diesel. The methanol fuel is stored within the Methanol System BG which was not included in the layout model for the same reason as the Diesel Supply BG. The assumption for both the Methanol and Diesel tanks to be distributed across the vessel is based upon the SPEC Analysis that showed that the volume required for the fuel is sufficient within the vessel's current tanks. Through the detailed operational analysis it was identified that the methanol volume limits needed are below the total volume available in the Use Case.

Moreover, the *Methanol Reformers BG* are responsible to extract the hydrogen from methanol fuel and *Hydrogen Supply BG* receives the hydrogen and distributes it the Fuel Cells. The only hydrogen on board is generated from the methanol reformers. As hydrogen in liquid form comes with associated hazards and can be explosive in the presence of oxygen, it was avoided to have hydrogen tanks. From the SPEC analysis performed from MARIN the main reason for selecting methanol over hydrogen was the contained energy density. Hydrogen has a much lower contained energy density than methanol. For storing hydrogen, high pressure gaseous tanks or liquid hydrogen tanks would have been needed. Having methanol fuel instead of hydrogen makes the whole safety system much more comprehensible. Methanol fuel is associated with safety hazard but still easier to manage when compared to hydrogen. *Fuel Cells* produce DC electricity that is connected to the *DC distribution BGs* and distribute DC across the PPE system in the necessary BGs. The two *ESM (Electric Shaft Machine) Converter BGs*, convert DC to AC from the DC distribution system and are connected to the two ESM Machines. An *AC Distribution BG* is responsible of distributing AC across the PPE system. The *ESM Machines BGs* convert the AC power to mechanical energy through the mechanical shafts connected to the *Mechanical transmission*.

The PPE consists of two *Lithium Ion Batteries BGs* that store electrical DC energy. A *Nitrogen Tank BG* is found necessary to be included to inert the methanol that has an explosive nature. It is a mitigation system to avoid explosion risks. Additionally, Nitrogen is used for purging to remove all the hydrogen from the connecting pipes and systems. Finally, a *Central Cooling Water BG* and a *Fresh Water Tank BG* are included in the PPE system. It is important to note that an exhaust after-treatment BG was decided not to included. Even though the exhaust after-treatment BG is often very large it is most often placed overhead above the main engines and the main level and therefore does not affect the 2D layout General Arrangements.

8
Use Case Testing

Now that the large motor yacht use case PPE system and the developed general arrangement optimization tool are fully elaborated, testings will be performed. This chapter investigates the research sub-question **4**.

The testings are divided in three different sections. In the first section testings will be performed based on a defined relative weight factor implemented to account for the different actual connection types. In the second section, tests will be performed based on the actual connection cost per meter of the connections. Finally, the last set of testings will be performed on a relationship matrix that aims to capture the relationship between BGs and not the actual connections. Prior to all these different tests a sensitivity analysis based on the actual PPE system was essential to ensure that the parameters used in the optimization tool are sufficient to provide accurate layout results within an appropriate time-frame.

8.1. PPE system Modeling

In table 8.1 all BG-related data captured as inputs for the optimization tool are shown. As already described in section 7.1.2 these include; the *BG name, ID, color, dimensions, margins, weight, I/O positions, rotational* and *positional constraints*. These have been collected from data of actual state of art marine equipment that can be used on board a novel PPE system. Margins have been decided based on the actual specification listed or based on law requirements. For instance, the DC and AC distribution systems are required by safety laws to have a $1.2m$ margin in the front side.

Table 8.1: PPE building groups of Use Case 10 for the general arrangement layout with all the defined modelling details

Building Group Name	Margins [m]				Dimensions [m]		Input/Output Position [m]				Rotational Constraint [0,1]	Positional Constraints [m]				Weights [kg]
	Margin	Right	Top	Bottom	Width	Length	X Input	X Output	Y Inputs	Y Output	AllowedToRotate	XMin	YMin	XMax	YMax	
Methanol Fuel Preparation	0.6	0	0.6	0	1.8	3	0	3	0.9	0.9	1	0	0	9.00E+99	7.5	1300
Diesel Day Supply	0	0	0.5	0	1	0.8	0	0.8	0.5	0.5	1	0	0	9.00E+99	7.5	1572
Hydrogen Supply	0.2	0.2	0.2	0.2	0.3	0.5	0	0.5	0.15	0.15	1	0	0	9.00E+99	7.5	100
Fuel Cell (1)	0	0	0.8	0.3	0.7	1.2	0.6	0.6	0.7	0.7	1	0	0	9.00E+99	7.5	875
Fuel Cell (2)	0	0	0.8	0.3	0.7	1.2	0.6	0.6	0.7	0.7	1	0	0	9.00E+99	7.5	875
Main Engine (1)	0.5	0.5	0.5	0.5	1.3	1.6	0.8	0	0.65	0.65	0	2.6	4.7	2.6	4.7	1349
Main Engine (2)	0.5	0.5	0.5	0.5	1.3	1.6	0.8	0	0.65	0.65	0	2.6	0.95	2.6	0.95	1349
ESM Converter (1)	0	0	0.5	0	0.4	0.3	0.15	0.15	0	0	1	0	0	9.00E+99	7.5	23
ESM Converter (2)	0	0	0	0.5	0.4	0.3	0.15	0.15	0	0	1	0	0	9.00E+99	7.5	23
ESM Machine (1)	0	0	0.5	0	0.7	1.2	0.6	0	0.35	0.35	0	0.9	5	0.9	5	950
ESM Machine (2)	0	0	0	0.5	0.7	1.2	0.6	0	0.35	0.35	0	0.9	1.25	0.9	1.25	950
DC Distribution (1)	0	0	1.2	0.3	0.6	4.4	2.2	2.2	0	0	1	0	0	9.00E+99	7.5	2300
DC Distribution (2)	0	0	1.2	0.3	0.6	4.4	2.2	2.2	0	0	1	0	0	9.00E+99	7.5	2300
AC Distribution	0	0	1.2	0.3	0.6	3	1.5	1.5	0	0	1	0	0	9.00E+99	7.5	1200
Battery (1)	0	0	0.8	0.3	0.7	6.9	3.45	3.45	0	0	1	0	0	9.00E+99	7.5	13024
Battery (2)	0	0	0.8	0.3	0.7	6.9	3.45	3.45	0	0	1	0	0	9.00E+99	7.5	13024
Nitrogen Tank	0	0	0.5	0	0.5	0.5	0.25	0.25	0.25	0.25	1	0	0	9.00E+99	7.5	368
Mechanical Transmission (1)	0	0	0.5	0	0.9	0.9	0.9	0	0.45	0.45	0	0	4.9	0	4.9	740
Mechanical Transmission (2)	0	0	0	0.5	0.9	0.9	0.9	0	0.45	0.45	0	0	1.15	0	1.15	740
Methanol Reformer (1)	0	0	0.8	0.3	1	2.1	0	0	0.5	0.5	1	0	0	9.00E+99	7.5	900
Methanol Reformer (2)	0	0	0.8	0.3	1	2.1	0	0	0.5	0.5	1	0	0	9.00E+99	7.5	900
Methanol Reformer (3)	0	0	0.8	0.3	1	2.1	0	0	0.5	0.5	1	0	0	9.00E+99	7.5	900
Methanol Reformer (4)	0	0	0.8	0.3	1	2.1	0	0	0.5	0.5	1	0	0	9.00E+99	7.5	900
Central Cooling Water	0	0	0.5	0	0.5	1	0	0	0.25	0.25	1	0	0	9.00E+99	7.5	500
Fresh Water Tank	0	0	0.5	0	0.5	1	0	0	0.25	0.25	1	0	0	9.00E+99	7.5	100
Exhaust Interface PS (1)	0	0	0	0	0.1	1	0.5	0.5	0	0	0	0	7.4	9.00E+99	7.4	0
Exhaust Interface SS (2)	0	0	0	0	0.1	1	0.5	0.5	0	0	0	0	0	9.00E+99	0	0
H2 Exhaust Interface	0	0	0	0	0.1	1	0.5	0.5	0	0	0	0	0	9.00E+99	0	0

8.2. Convergence Analysis/ Tuning Parameters

Before performing the actual use case tests it was essential to ensure that the appropriate algorithms tuning parameters have been selected. Therefore a convergence analysis is performed on the defined use case PPE system. The convergence study was performed using the connection weight matrix which will be clarified in detail in section 8.3. Convergence study was only necessary to be performed on the first GA and only for the first set of tests with 28 BGs/interfaces and a total of 84 dimensions. For all other implemented algorithms the default MATLAB settings have been used. Additionally, for the simplified PPE systems where BGs are grouped (problem dimensions are decreased to 72) presented in section 8.3.4, the default Matlab settings for the first GA were considered highly sufficient as well.

8.2.1. First GA

As explained in section 7.2.1 the first part of the hybrid algorithm uses Deb's NSGA-II directly obtained from MATLAB's global optimisation toolbox [108]. Numerous initial runs were executed to observe the model's behaviour of the model In these runs few critical tuning parameters were examined for handling the highly multi-dimensional model. As already mentioned in section 7.1.3, the initial tests are performed with 28 BGs/interfaces and therefore the model has a total of 84 dimensions. The crucial tuning parameters that were examined are the *Population size*, *Maximum Stall Generations*, *Maximum Generations* and *Function Tolerance*.

- Population size: Is the size of the population in each generation.
- Maximum Stall Generations and Function Tolerance: The algorithm stops when the geometric average of the relative change in value of the spread over Maximum Stall Generations generations is less than Function Tolerance, and the final spread is less than the mean spread over the past Maximum Stall Generations generations.
- Maximum Generations: Maximum number of iterations before the algorithm halts.

The first genetic algorithm starts with finding random feasible layouts. It avoids all constraints by default. Any random layouts created that do not obey the constraints are discarded and new random layouts are created until all constraints are satisfied. These initial layouts are inefficient with a lot of spacing between the BGs. The latter steps in the hybrid algorithm developed aim to optimize these inefficiencies. In summary, with the first GA it is aimed to have a variety of feasible layouts that can later be optimized and produce better layout results. Therefore, the most important outcome of the first GA is the number of layouts generated. Figures 8.1, 8.2 and 8.3, illustrate the effect of only changing the population size and keeping the other parameters constant at their default values. The default MATLAB's GA population size is 200. The total connection cost and the engine room's length show an overall decrease when the population size increases. However, from a population size of 800 onward, the decrease effect seems to vanish. The number of solutions seem not to correlate with the population size as in each run the number of solutions randomly increase or decrease. Population size of 1200 is discarded as only 1 feasible solution is generated and this would seriously limit the algorithm's final results. Population size of 800 or 1000 seem to be the two best options as they have a sufficient number of generated solutions, relatively low connection cost and length.

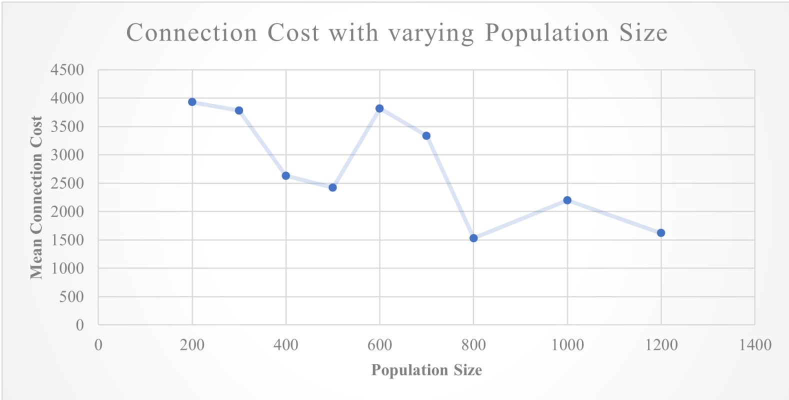


Figure 8.1: Population size effect on Connection cost

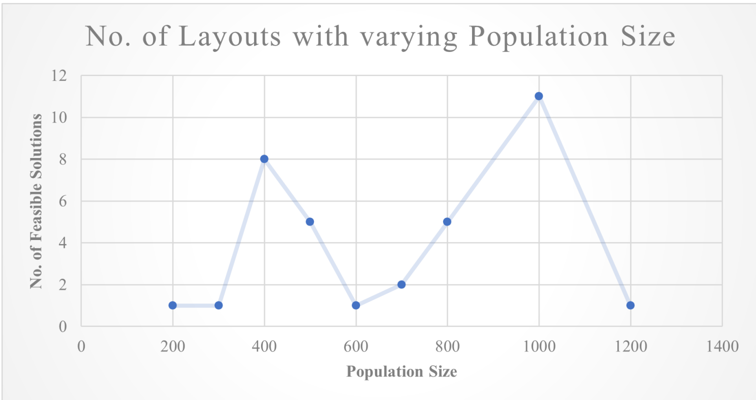


Figure 8.2: Population size effect on feasible generated PPE system layouts

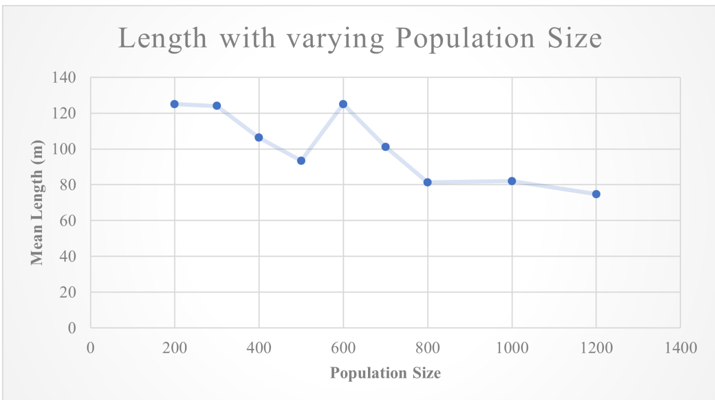


Figure 8.3: Population size effect on engine room length

Figures 8.4, 8.5 and 8.6, illustrate the effect of changing the maximum stall generations with fixed population size of 200 (MATLAB's default). A clear link between the increase in maximum stall generations and the decrease in total connection cost and length is depicted. A convergence effect that flattens out at about 800 maximum stall generations is observed. Again the number of solutions show no correlation with increasing of maximum stall generations. 700 and 800 Maximum Stall generations obtain the best results and will be further tested with the promising population size of 800 and 1000.

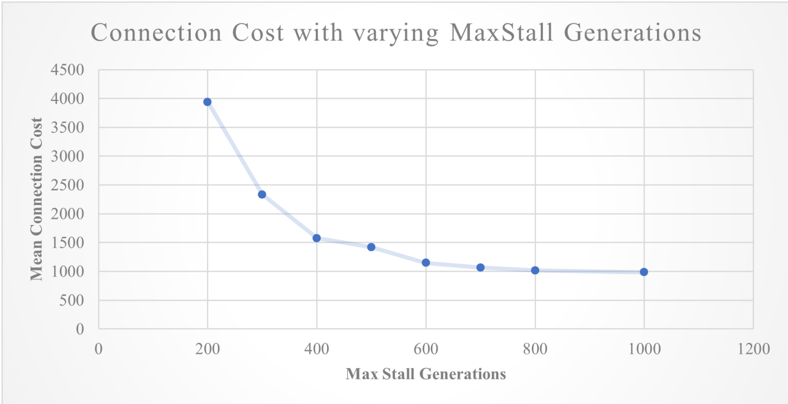


Figure 8.4: Maximum Stall Generations effect on Connection cost

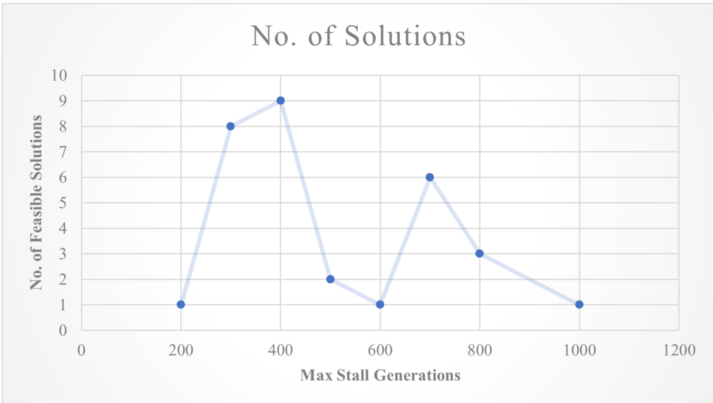


Figure 8.5: Maximum Stall Generations effect on feasible generated PPE system layouts

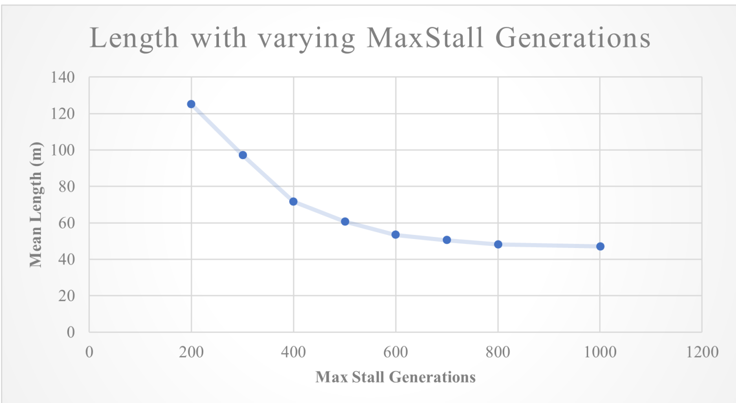


Figure 8.6: Maximum Stall Generations effect on engine room length

From the performed convergence study, the chosen parameters for both population size (800 & 1000) and maximum stall generations (700 & 800) have been tested in the different possible combinations. The results of these four different tests are presented in table 8.2.

Table 8.2: Tests on selected tuning parameters

Population Size	Max Stall Generations	No. of Solutions	Mean Connection Cost	Mean Length (m)
800	700	7	1377.22	71.59
1000	700	3	920.91	38.17
800	800	4	1334.26	69.2
1000	800	1	905.25	36

Consequently, when investigating the generated results the population size of 800 and maximum stall generations of 700 have been chosen. As seen clearly from table 8.2, the population size of 1000 in both cases had a positive effect both on minimum connection cost and engine room's length. However, the number of generated layouts on these two tests was low. The reason for that is that with the additional population size the solutions may further converge and reproduce leading to similar solutions and the design tool has been designed to discard very similar solutions at the end of each solver to ensure that identical layouts are not generated. As a result this highly limits the algorithm's exploration on the next steps and the ability to generate several different PPE system layouts. Therefore, these parameter combinations were discarded. The most important outcome, that is of great importance from the first GA is the number of solutions that can be generated for further exploration in the following steps.

Finally, the effect of maximum generations was investigated and it was observed that it had no effect on the algorithm, as none tests were terminated due to maximum generation being reached. The default MATLAB's setting of maximum generations was used. The default value is $(200 \times \text{number of Variables})$, which is equivalent to 16800 generations.

8.3. Connection Weight Matrix

In this section the first type of tests performed on the PPE system are presented. The CM_{ij} factor, explained in section 7.1.1 has been firstly implemented as a relative weight factor indicating the connection importance based on its physical type.

8.3.1. Defined Dimensions and Margins

Before the investigation of the first type of tests it is important to address how the BGs dimensions and margins have been defined. Firstly, all BGs dimensions are derived from actual dimensions of state of the art components that can be found in the maritime industry and have been used within MARIN for previous design projects. Secondly, all margins or clearance spaces are derived from the actual official specifications requirements of the specific components, derived from rules and regulations, or have been carefully chosen from discussions within MARIN. For instance, for the DC and AC distribution BGs a $1.2m$ was defined on the front side, as this specified clearance space is advised by *Lloyd's Rules and Regulations for the Classification of ships*. All the detailed BGs dimensions and clearance spaces selected can be seen in table 8.1.

After the generation of numerous exploration layouts to test the response of the model and careful reading some margins alterations were conducted. Specific margins have been removed and these are illustrated with red font in table 8.3. All electrical components, methanol reformers and fuel cells had a dedicated back-side margin for the necessary space provision of the different cables. These specified margins cannot be overlapped with other margins and it was therefore decided to remove these margins and increasing the BGs dimensions. Moreover, from specification requirements the main engines had an all around defined clearance space of $0.5m$. However, the margin facing towards the gearbox (left) has been decided to be removed. It was found unnecessary to include this specific margin for the 2D arrangement layouts as it is used to account for the gearbox placement which is positioned overhead, at a higher level than the main engine.

Table 8.3: PPE building groups defined margins. Margins highlighted in red have been removed and directly added as additional dimension on the equivalent Building Groups

Building Group Name	Margins [m]			
	Left	Right	Top	Bottom
Methanol Fuel Preparation	0.6	0	0.6	0
Diesel Day Supply	0	0	0.5	0
Hydrogen Supply	0.2	0.2	0.2	0.2
Fuel Cell (1)	0	0	0.8	0.3
Fuel Cell (2)	0	0	0.8	0.3
Main Engine (1)	0.5	0.5	0.5	0.5
Main Engine (2)	0.5	0.5	0.5	0.5
ESM Converter (1)	0	0	0.5	0
ESM Converter (2)	0	0	0	0.5
ESM Machine (1)	0	0	0.5	0
ESM Machine (2)	0	0	0	0.5
DC Distribution (1)	0	0	1.2	0.3
DC Distribution (2)	0	0	1.2	0.3
AC Distribution	0	0	1.2	0.3
Battery (1)	0	0	0.8	0.3
Battery (2)	0	0	0.8	0.3
Nitrogen Tank	0	0	0.5	0
Mechanical Transmission (1)	0	0	0.5	0
Mechanical Transmission (2)	0	0	0	0.5
Methanol Reformer (1)	0	0	0.8	0.3
Methanol Reformer (2)	0	0	0.8	0.3
Methanol Reformer (3)	0	0	0.8	0.3
Methanol Reformer (4)	0	0	0.8	0.3
Central Cooling Water	0	0	0.5	0
Fresh Water Tank	0	0	0.5	0
Exhaust Interface PS (1)	0	0	0	0
Exhaust Interface SS (2)	0	0	0	0
H2 Exhaust Interface	0	0	0	0

8.3.2. Connections

Within a vessel's engine room there are numerous connections of different types. These can vary from electrical cables, to fuel pipes, up to mechanical shaft. Therefore, when designing the PPE system it was found essential that not all connections are treated equally. The specific values assigned for the different physical connections have been chosen after discussions within MARIN. For instance, it has been depicted that the mechanical shaft is the most important connection that needs to be minimized and is represented with a CM value of 5. In the same way the electrical power cables have been found to be relatively unimportant and CM of 1 has been chosen to depict these electrical connections. All relative weight values between 1-5 that were assigned are shown in detail in table 8.5.

The equivalent connection matrix is illustrated in figure 8.7. A higher weight value symbolizes a higher importance connection and the design arrangement tool prioritizes the minimization of these connections. This weight is multiplied with the manhattan connection distance. The total sum of all the distances after being multiplied with this distributed weight is the total connection cost that the second objective aims to minimize.

In table 8.4, the numerous detailed connections between the PPE system's BGs taken into consideration in the design tool are depicted. The interface information are obtained from the large motor yacht's MBSE physical architecture. As clearly specified in section 5.1.1, a sub-question generated from the main research question was to investigate the level of detail of the physical properties captured. These include the level of detail of the different connection interfaces between the BGs across the PPE system. The MBSE physical architecture can capture an enormous amount of detail and include all PPE system's details and connections.

Here is important to note that in reality in table 8.4 and consequently in the design tool, more connections could have been captured from the MBSE physical architecture. For instance, a connection that was not taken into consideration is the lube oil supply from the tank to the main engines that is responsible for the lubrication and cooling of the engines internal parts. Moreover, the control cables that have the function to send signals to control the functioning of the different BGs were excluded.

These are not considered in this study as the focus is on the most relevant connections. However, seemingly unimportant connections may also be relevant nevertheless. Simplifications in the level of the connections detail were iteratively taken through continuous discussion with MARIN throughout the thesis project.

By capturing more and more interfaces the relative importance of critical connections that can have significant effect on the design layout from the conceptual design stage can reduce. This in return, can diminish the effect of the design tool to arrange the PPE system layouts by prioritizing important BGs connections. For instance, hydrogen piping across the PPE system within the engine room is usually chosen to be minimized. Consequently, the hydrogen piping connections directly affect the PPE system design, leading to configurations were hydrogen supply BG and fuel cells BGs are located nearby.

Additionally, as clearly seen from table 8.4, within the PPE system there are several different water cooling piping connections such as low (LT), medium temperature (MT) and raw water (RW). In some BGs, such as the batteries more than one type of water piping flows in and out. It was found unnecessary to capture the different types of the cooling water connections for a single BG and therefore the water piping connections flowing in and out of these BGs was simplified as a single water connection.

Finally, as presented at the bottom of table 8.4, few important interfaces that are positioned on the ship's side walls have been decided to be modelled in the PPE system. These include the port (PS) and starboard side (SS) exhaust interface and the hydrogen interface. Even if these are not included in the MBSE physical architecture and are not actual BGs, they capture crucial exhaust connections and therefore have been included in the PPE system model.

Table 8.4: All modelled analytical interfaces between the building groups

Building Group	Inputs	Input From:	Outputs	Output To:
Methanol Fuel Preparation	Diesel Piping AC Power Cable Fresh Water Piping	Diesel Day Supply AC Distribution Fresh Water Tank	Fuel Piping	Main Engines (1)(2)
Diesel Day Supply	AC Power Cable	AC Distribution	Diesel Piping	Methanol Fuel Preparation
Hydrogen Supply	Purging Gas Inlet (N_2 Piping) H_2 Piping	Nitrogen Tank Methanol Reformer	H_2 Venting H_2 Piping	Open deck(H_2 Exhaust Interface) Fuel Cell (1) (2)
Fuel Cell (1)	H_2 Piping AC Power Cable RW Inlet MT Inlet	Hydrogen Supply AC Distribution Central Cooling water Central Cooling water	Anode Exhaust Stack (H_2) DC Power Cable Cathode Exhaust (H_2O) RW Outlet MT Outlet	Open deck (H_2 Exhaust Interface) DC Distribution Methanol Fuel Preparation Central Cooling Water Central Cooling Water
Fuel Cell (2)	H_2 Piping AC Power Cable RW Inlet MT Inlet	Hydrogen Supply AC Distribution Central Cooling water Central Cooling water	Anode Exhaust Stack (H_2) DC Power Cable Cathode Exhaust (H_2O) RW Outlet MT Outlet	Open deck (H_2 Exhaust Interface) DC Distribution Methanol Fuel Preparation Central Cooling Water Central Cooling Water
Main Engine (1)	Fuel Piping Ignition Fuel Piping RW Inlet	Methanol Fuel Preparation Diesel Day Supply Central Cooling water	Mechanical Shaft Engine Exhaust RW Outlet	ESM Machine (1) Exhaust Interface PS (1) Central Cooling Water
Main Engine (2)	Fuel Piping Ignition Fuel Piping RW Inlet	Methanol Fuel Preparation Diesel Day Supply Central Cooling water	Mechanical Shaft Engine Exhaust RW Outlet	ESM Machine (2) Exhaust Interface PS (2) Central Cooling Water
ESM Converter (1)	DC Power Cable MT Inlet	DC Distribution Central Cooling water	AC Power Cable MT Outlet	ESM Machine Central Cooling Water
ESM Converter (2)	DC Power Cable MT Inlet	DC Distribution Central Cooling water	AC Power Cable MT Outlet	ESM Machine Central Cooling Water
ESM Machine (1)	AC Power Cable MT Inlet Mechanical Shaft	ESM Converter (1) Central Cooling water Main Engine (1)	Mechanical Shaft MT Outlet	Mechanical Transmission (1) Central Cooling Water
ESM Machine (2)	AC Power Cable MT Inlet Mechanical Shaft	ESM Converter (2) Central Cooling water Main Engine (2)	Mechanical Shaft MT Outlet	Mechanical Transmission (2) Central Cooling Water
DC distribution (1)	DC input cable	Fuel Cell	DC output cable	ESMC(x2)/ Batteries(x2) / AC / DC
DC distribution (2)	DC input cable	Fuel Cell	DC output cable	ESMC(x2)/ Batteries(x2) / AC / DC
AC distribution	AC input cable	DC Distribution	AC output cable	MFP / DDS/ FC(x2) / ESMM(x2)
Battery (1)	DC Power Cable MT Inlet LT Inlet	DC Distribution Central Cooling water Central Cooling water	DC Power Cable MT Outlet LT Outlet	DC Distribution Central Cooling Water Central Cooling Water
Battery (2)	DC Power Cable MT Inlet LT Inlet	DC Distribution Central Cooling water Central Cooling water	DC Power Cable MT Outlet LT Outlet	DC Distribution Central Cooling Water Central Cooling Water
Nitrogen Tank			N_2 piping	Hydrogen Supply
Mechanical Transmission (1)	Mechanical Shaft	Main Engine (1) and ESM Machine (1)	Mechanical Shaft	Propeller(fixed point at aft)
Mechanical Transmission (2)	Mechanical Shaft	Main Engine (2) and ESM Machine (2)	Mechanical Shaft	Propeller(fixed point at aft)
Methanol Reformer (1)	Methanol Piping	Methanol System	H_2 Piping	Hydrogen Supply
Methanol Reformer (2)	Methanol Piping	Methanol System	H_2 Piping	Hydrogen Supply
Methanol Reformer (3)	Methanol Piping	Methanol System	H_2 Piping	Hydrogen Supply
Methanol Reformer (4)	Methanol Piping	Methanol System	H_2 Piping	Hydrogen Supply
Central cooling water	Sea Water LT Inlet MT Inlet RW Inlet	(from sea) Batteries FCs/ESM Conv./ESM Mach./Batteries FCs/MEs	LT Outlet MT Outlet RW Outlet	Batteries FCs/ESM Conv./ESM Mach./Batteries FCs/MEs
Fresh Water Tank	Fresh Water Piping	Methanol Fuel Preparation	Fresh Water Piping	Methanol Fuel Preparation
Exhaust ***Interface*** PS (1)	Engine Exhaust	Main Engine (1)		
Exhaust ***Interface*** SS (2)	Engine Exhaust	Main Engine (2)		
H_2 Exhaust ***Interface***	Anode Exhaust Stack (H_2) H_2 Venting	Fuel Cells (1) (2) Hydrogen Supply		

Table 8.5: Assigned matrix weights based on the physical defined connections

Connection Matrix Weight				
1	*2*	*3*	*4*	*5*
AC Power Cable	Fuel Piping	Hydrogen Supply		Mechanical Shaft
DC Power Cable	Medium Temp. H_2O Inlet/Outlet	Engine Exhaust		
Diesel Piping	Low Temp. H_2O Inlet/Outlet	Anode Exhaust H_2		
Ignition Fuel Piping	Raw H_2O Inlet/Outlet			
Cathode Exhaust H_2O	Fresh Water Piping			
N_2 Piping				

		j Component - Input																										
		Methanol Fuel Preparation	Diesel Day Supply	Hydrogen Supply	Fuel Cell (1)	Fuel Cell (2)	Main Engine (1)	Main Engine (2)	ESM Converter (1)	ESM Converter (2)	ESM Machine (1)	ESM Machine (2)	DC distribution (1)	DC distribution (2)	AC distribution (1)	Battery (1)	Battery (2)	Nitrogen Tank	Mechanical Transmission (1)	Mechanical Transmission (2)	Methanol Reformer (1)	Methanol Reformer (2)	Methanol Reformer (3)	Methanol Reformer (4)	Central Cooling Water	Fresh Water Tank	Exhaust Exit (1)	Exhaust Exit (2)	H2 Open Deck Exit
i Component - Output	Methanol Fuel Preparation		0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Diesel Day Supply	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Hydrogen Supply	0	0		3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
	Fuel Cell (1)	1	0	0		0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	3
	Fuel Cell (2)	1	0	0	0		0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	3
	Main Engine (1)	0	0	0	0	0		0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	3	0	0
	Main Engine (2)	0	0	0	0	0	0		0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	3	0
	ESM Converter (1)	0	0	0	0	0	0	0		0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
	ESM Converter (2)	0	0	0	0	0	0	0	0		0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
	ESM Machine (1)	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	5	0	0	0	0	0	2	0	0	0	0
	ESM Machine (2)	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	5	0	0	0	0	2	0	0	0	0
	DC distribution (1)	0	0	0	0	0	0	0	1	0	0	0		1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	DC distribution (2)	0	0	0	0	0	0	0	0	1	0	0	1		1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	AC distribution (1)	1	1	0	1	1	0	0	0	0	1	1	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Battery (1)	0	0	0	0	0	0	0	0	0	0	0	1	0	0		0	0	0	0	0	0	0	0	2	0	0	0	0
	Battery (2)	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0		0	0	0	0	0	0	0	2	0	0	0	0
	Nitrogen Tank	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0
	Mechanical Transmission (1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0
	Mechanical Transmission (2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0
	Methanol Reformer (1)	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
	Methanol Reformer (2)	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0
	Methanol Reformer (3)	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
	Methanol Reformer (4)	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0
	Central Cooling Water	0	0	0	2	2	2	2	2	2	2	2	0	0	0	2	2	0	0	0	0	0	0	0		0	0	0	0
	Fresh Water Tank	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0
	Exhaust Exit (1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
	Exhaust Exit (2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
	H2 Open Deck Exit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Figure 8.7: Defined Connection Matrix

8.3.3. Test 1: Initial Test with the 28 defined BGs

In test 1 the assigned CM values and the detailed analytical interfaces illustrated in tables 8.5 and 8.4 are modelled. The two best layouts in terms of minimum total connection cost $(TCC = 536.6)$ and minimum length $(Length = 17.6m)$ are presented in layout figures 8.8 and 8.10 respectively. In figures 8.9 and 8.11 the same PPE system layouts are presented including all major connections $(CM_{ij} \geq 3)$. These include the mechanical shaft and hydrogen piping, the engine exhaust and the hydrogen exhaust from the fuel cells and the hydrogen supply BG.

Table 8.6: All BGs modelled with their equivalent number code

	BlockName
1	"Methanol Fuel Preparation"
2	"Diesel Day Supply"
3	"Hydrogen Supply"
4	"Fuel Cell (1)"
5	"Fuel Cell (2)"
6	"Main Engine (1)"
7	"Main Engine (2)"
8	"ESM Converter (1)"
9	"ESM Converter (2)"
10	"ESM Machine (1)"
11	"ESM Machine (2)"
12	"DC Distribution (1)"
13	"DC Distribution (2)"
14	"AC Distribution (1)"
15	"Battery (1)"
16	"Battery (2)"
17	"Nitrogen Tank"
18	"Mechanical Transmission (1)"
19	"Mechanical Transmission (2)"
20	"Methanol Reformer (1)"
21	"Methanol Reformer (2)"
22	"Methanol Reformer (3)"
23	"Methanol Reformer (4)"
24	"Central Cooling Water"
25	"Fresh Water Tank"
26	"Exhaust Interface PS (1)"
27	"Exhaust Interface SS (2)"
28	"H2 Exhaust Interface"

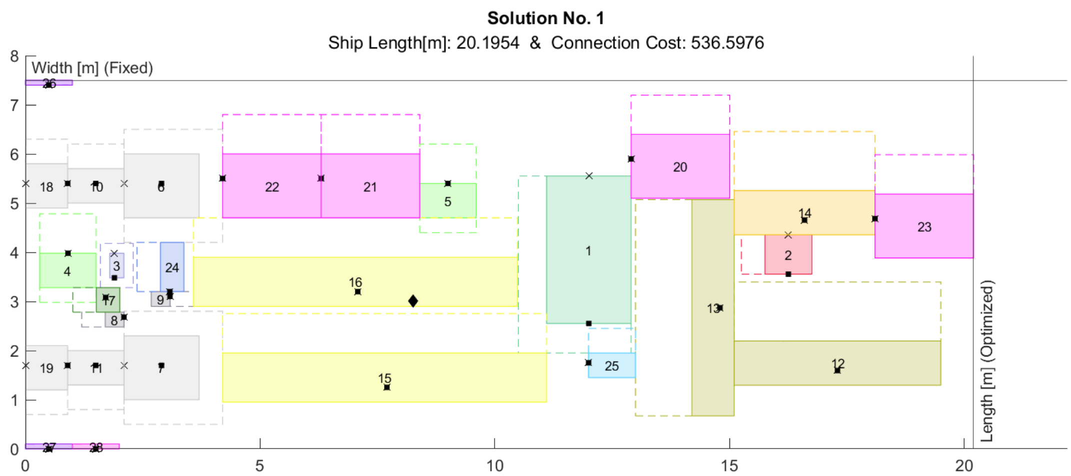


Figure 8.8: Test 1 layout arrangement with the lowest total connection cost $(TCC = 536.6)$

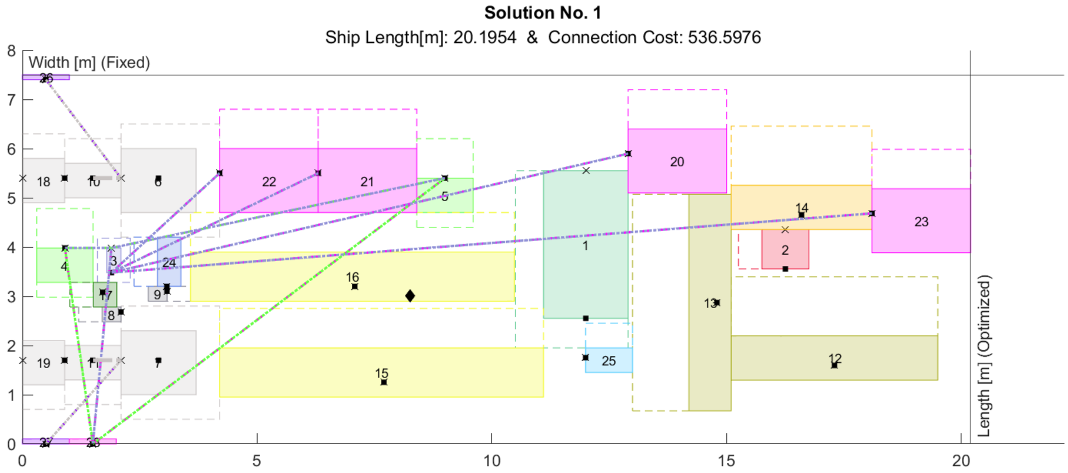


Figure 8.9: Test 1 layout arrangement including major connections with the lowest total connection cost $(TCC = 536.6)$

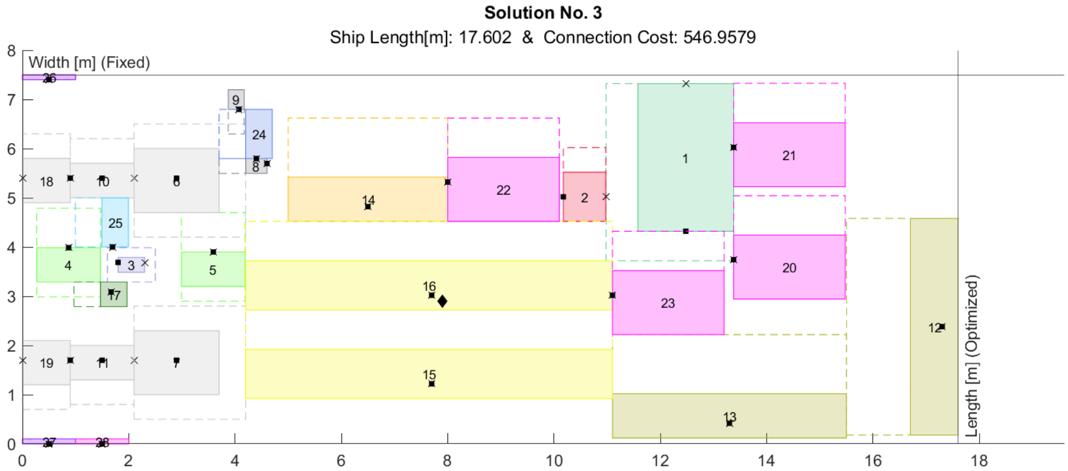


Figure 8.10: Test 1 layout arrangement with the most optimized engine room length $(Length = 17.6m)$

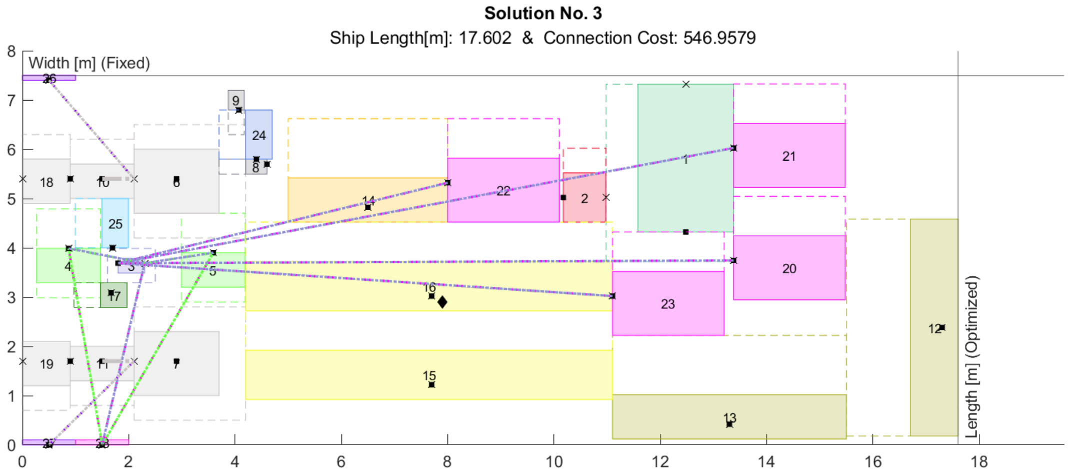


Figure 8.11: Test 1 layout arrangement including major connections with the most optimized engine room length $(Length = 17.6m)$

When observing the generated PPE system arrangements important conclusions can be drawn. Firstly, it can be clearly seen that the PPE system arrangement tool well optimizes the BGs across the engine room space, leaving minimal engine room space not being utilized. However, while the design tool tries to exploit all the free space, chaotic layouts are created, which are not practical in real case design scenarios. This chaotic effect is created due to two main reasons.

Firstly, an underlying reason for these chaotic layouts, is that **the model does not 'reward' grouping building groups of the same kind to be close together, which can in return simplify the connections.** The design tool does not recognise the connection cost of parallel connections of the same family that can be merged as one larger connection and minimize complexity. For instance, in reality the ship designers will choose to group together the four methanol reformers within a PPE system. This will enable the four hydrogen pipes to be combined in a larger pipe set. This will result in a further reduction in the hydrogen piping connection costs as a larger pipe set will have a lower cost than four smaller pipes. Additionally, the methanol reformers need to be avoided to be placed randomly across the PPE system, as there is a significant hazard associated with having hydrogen piping all over the engine room.

This chaotic effect is tackled in section 8.3.4. It can be noted, that in some generated PPE layouts, such as the layout shown in figure 8.12, the tool positioned the four methanol reformers and the two fuel cells in a neat and orderly arrangement, minimizing the chaotic nature of the layout. However, this is not often the case for most generated PPE layouts.

Additionally, when investigating the generated layouts in some cases, minor manual changes are essential from the ship designers to further improve the layouts. For example, when observing figure 8.12, rotating 90 degrees the first DC distribution BG can have a direct decrease of $2.3m$ in the engine room length, resulting to a final engine room length of $17.7m$. As clearly specified the design tool is used during the conceptual design stage to create some first initial general arrangement plans of the PPE system, within the engine room. Some manual adjustments might therefore be necessary.

Secondly, **the design tool treats all BGs equally and positions them as closely packed as possible.** This in return creates some unrealistic BGs arrangements. From the first layouts shown in the figures, while the PPE system design tool greatly exploits the engine room area leaving minimal unused space, the close positioning of certain BGs should be avoided. For instance, in these layouts the hydrogen supply is positioned between the Main Engines. In reality due to the low auto-ignition temperatures of hydrogen, the hydrogen supply should be avoided to be placed nearby hot surfaces such as the main engines and exhausts piping. These kind of relationships cannot be understood by the design tool that treats all BGs equally.

A solution to this effect can be to partially positionally constraining certain BGs to certain engine room regions. As already discussed in section 7.1.2, the design tool has the ability to either fully or partially constrain BGs. For instance, a partial positional constraint on the hydrogen supply BG, can be that the BG cannot be positioned somewhere within the first 5 meters of the engine room's x-axis. This will ensure that the hydrogen BG is nowhere near the MEs. The partial/fully constraint can act as a measure of (pseudo)creating compartments within an engine room. It can be similar to having certain dedicated spaces for some BGs. For instance, a dedicated room for the batteries can be present in a novel PPE system engine room and therefore the batteries can be assigned to a certain place by applying positional constraints.

However, for the first tests it has been chosen not to apply any positional constraints on the BGs that can restrict the arrangement freedom of the PPE system layouts. The fundamental and initial aim of the design tool is to explore the various PPE system layout possibilities that can be generated and to provide initial design insights. Positional constraints can implemented on a later stage.

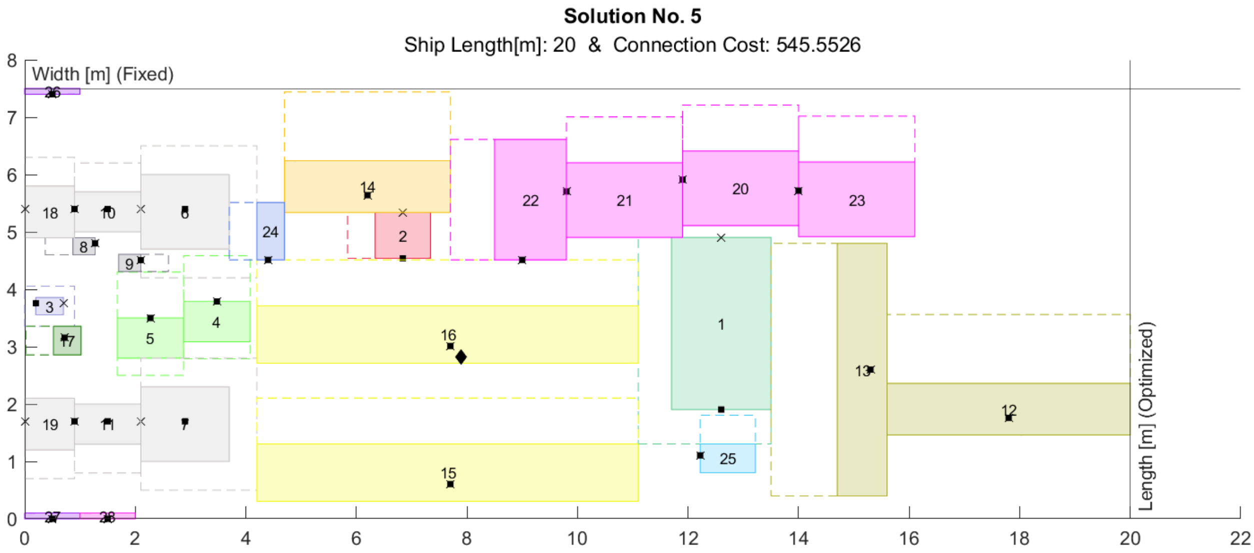
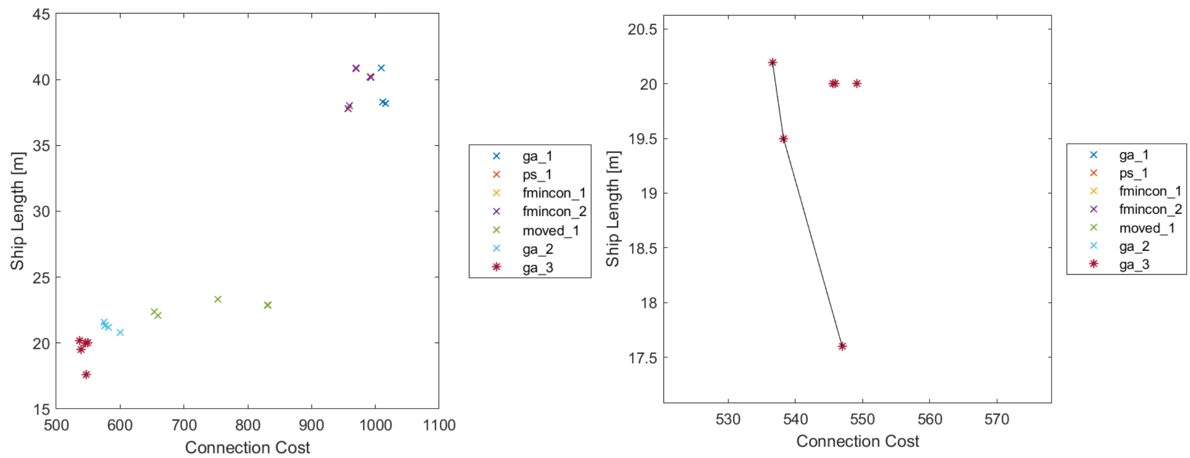


Figure 8.12: Test 1 layout arrangement

The PPE system tool generated 6 different PPE system GAP layouts. These are highlighted with a red star in sub-figure 8.13a which illustrates all the solutions on one graph against the two objective functions. The red stars on the scatter graph are the PPE system GAPs obtained after the final step of the design tool, the third Genetic Algorithm. It can be seen that the design tool successfully converges the PPE system throughout the different algorithm's steps. In sub-figure 8.13b, a close up of the same scatter graph is shown with the drawn pareto front line. As clearly seen, the design tool in this case generated 3 non-dominated solutions. All tool's GAPs, detailed tables and pareto figure are presented in Appendix B.1.



(a) All feasible PPE system solutions in one plot

(b) Pareto front

Figure 8.13: All feasible PPE system solutions

8.3.4. Tests 2: Methanol Reformers and Fuel Cells grouped

In the generated layouts illustrated from the initial tests the four methanol reformers and the two fuel cells are randomly placed within the engine room and in most cases located far apart from each other. In reality this is far from practical as identical BGs are in most cases grouped together within a PPE system in an organized manner. Within an engine room and in a novel PPE system where several unique BGs are included with numerous interconnections complexity can be substantial. Ship designers often choose to group identical BGs and their physical connections together to limit this unnecessary and avoidable complexity. For instance, when MRs are located randomly across the engine room, the disorganized and random lay out of hydrogen piping across the PPE system can become a serious concern when performing a safety/hazard assessment.

After obtaining the first generated layouts it has been decided to group the four Methanol Reformers and the two Fuel Cells together. The MRs and the FCs can either be placed in series by connected side to side or they can be placed back to back. This would minimize the chaotic nature of the already generated PPE system layouts. Therefore, in the design tool, the MRs and the FCs are both represented as one BG. After the grouping simplification, the each new grouped BG has one defined input and one defined output location. These have been carefully defined to be in the geometrical mean position of the actual four defined I/O points for the MRs or the two defined points of the FCs I/O points. Furthermore, the CM weight factors have been added as seen in bold in figure 8.14. For instance, the hydrogen piping connections between the grouped FCs and the hydrogen supply has been simplified from two connections with a corresponding CM value of 3 to one connection with a newly assigned CM value of 6.

As explained in the previous section 8.3.3 the actual cost does not double or quadruple when merging two or four pipes. However, in these tests we deal with CM weight factors and not the actual connections costs. The hazard and/or importance associated with one larger connection instead of four smaller is not minimized. Additionally, by keeping the same total sum of the CM weight values distributed, a direct comparison on the total connection cost between layouts of test 1 and 2 can be performed. This enables observations on the total connection cost effect when BGs of the same family are merged within a PPE system.

The new defined connection matrix and the BGs table the their equivalent number code are highlighted in figure 8.14 and table 8.15 respectively.

i Component - Output \ *j Component - Input*	Methanol Fuel Preparation	Diesel Day Supply	Hydrogen Supply	Fuel Cells	Main Engine (1)	Main Engine (2)	ESM Converter (1)	ESM Converter (2)	ESM Machine (1)	ESM Machine (2)	DC distribution (1)	DC distribution (2)	AC distribution	Battery (1)	Battery (2)	Nitrogen Tank	Mechanical Transmission (1)	Mechanical Transmission (2)	Methanol Reformers	Central Cooling Water	Fresh Water Tank	Exhaust Exit (1)	Exhaust Exit (2)	H2 Open Deck Exit
Methanol Fuel Preparation		0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel Day Supply	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hydrogen Supply	0	0		**6**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Fuel Cells	**2**	0	0		0	0	0	0	0	0	**2**	**2**	0	0	0	0	0	0	0	**4**	0	0	0	**6**
Main Engine (1)	0	0	0	0		0	0	0	5	0	0	0	0	0	0	0	0	0	0	2	0	3	0	0
Main Engine (2)	0	0	0	0	0		0	0	0	5	0	0	0	0	0	0	0	0	0	2	0	0	3	0
ESM Converter (1)	0	0	0	0	0	0		0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
ESM Converter (2)	0	0	0	0	0	0	0		0	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0
ESM Machine (1)	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	5	0	0	2	0	0	0	0
ESM Machine (2)	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	5	0	2	0	0	0	0
DC distribution (1)	0	0	0	0	0	0	1	0	0	0		1	1	1	0	0	0	0	0	0	0	0	0	0
DC distribution (2)	0	0	0	0	0	0	0	1	0	0	1		1	0	1	0	0	0	0	0	0	0	0	0
AC distribution	1	1	0	**2**	0	0	0	0	1	1	0	0		0	0	0	0	0	0	0	0	0	0	0
Battery (1)	0	0	0	0	0	0	0	0	0	0	1	0	0		0	0	0	0	0	2	0	0	0	0
Battery (2)	0	0	0	0	0	0	0	0	0	0	0	1	0	0		0	0	0	0	2	0	0	0	0
Nitrogen Tank	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
Mechanical Transmission (1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0
Mechanical Transmission (2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
Methanol Reformers	0	0	**12**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0
Central Cooling Water	0	0	0	**4**	2	2	2	2	2	2	0	0	0	2	2	0	0	0	0		0	0	0	0
Fresh Water Tank	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0
Exhaust Exit (1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
Exhaust Exit (2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
H2 Open Deck Exit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Figure 8.14: New defined Connection Matrix with grouped MRs and FCs

	BlockName
1	"Methanol Fuel Preparation"
2	"Diesel Day Supply"
3	"Hydrogen Supply"
4	"Fuel Cells"
5	"Main Engine (1)"
6	"Main Engine (2)"
7	"ESM Converter (1)"
8	"ESM Converter (2)"
9	"ESM Machine (1)"
10	"ESM Machine (2)"
11	"DC Distribution (1)"
12	"DC Distribution (2)"
13	"AC Distribution (1)"
14	"Battery (1)"
15	"Battery (2)"
16	"Nitrogen Tank"
17	"Mechanical Transmission (1)"
18	"Mechanical Transmission (2)"
19	"Methanol Reformers"
20	"Central Cooling Water"
21	"Fresh Water Tank"
22	"Exhaust Interface PS (1)"
23	"Exhaust Interface SS (2)"
24	"H2 Exhaust Interface"

Figure 8.15: New Building Group Table

Figures 8.16 and 8.18 represent the arrangement layout with the lowest total connection cost $(TCC = 494.7)$ and the most optimized engine room length $(Length = 15.7m)$ respectively. Numerous arrangement layouts from test 2 are presented in Appendix B.1.

In Test 2, with the FCs and MRs grouped together, a decrease in the chaotic nature of the arrangement layouts is clearly visible. When the BGs are arranged in an orderly manner a significant decrease both in the total engine room length and in the total connection cost can be achieved. Additionally, it can be seen that the best PPE system layouts both in terms of lowest connection cost and the minimum engine room length, are achieved when both the fuel cells and the methanol reformers are placed back to back on not in a long series configuration. Both MRs and FCs when positioned in a back to back square configuration, they can be more flexibly rearranged between different BGs leading to a higher utilization of engine room space. This is an important initial design insight obtained from the design tool and therefore these specific square configurations of the MRs and FCs system will be adapted for the following tests.

When investigating the PPE system layout in figure 8.19, that generated the shortest engine room length, with some minor manual changes it can further be optimized and represent an ideal PPE configuration. BGs with number 3 and 16, representing the hydrogen supply and the nitrogen tank BG respectively, can be manually placed in the empty space below BG number 1, the methanol reformer preparation BG. This will highly improve the total connection cost as seen from the major connections and will arrange the hydrogen supply BG in a better position, away from the MEs.

In figures 8.20 - 8.23 the scatter plots with all the different PPE system solutions generated are presented. The different scatter plots represent the different configurations of the MRs and the FCs tested. In all plots, a successful convergence behaviour of the design tool in optimizing the two objectives is observed. As noticed from the two axes in sub-figure 8.23b, the best PPE system layouts both in terms of lowest connection cost and the minimum engine room length, are achieved when both the fuel cells and the methanol reformers are placed in back to back configuration.

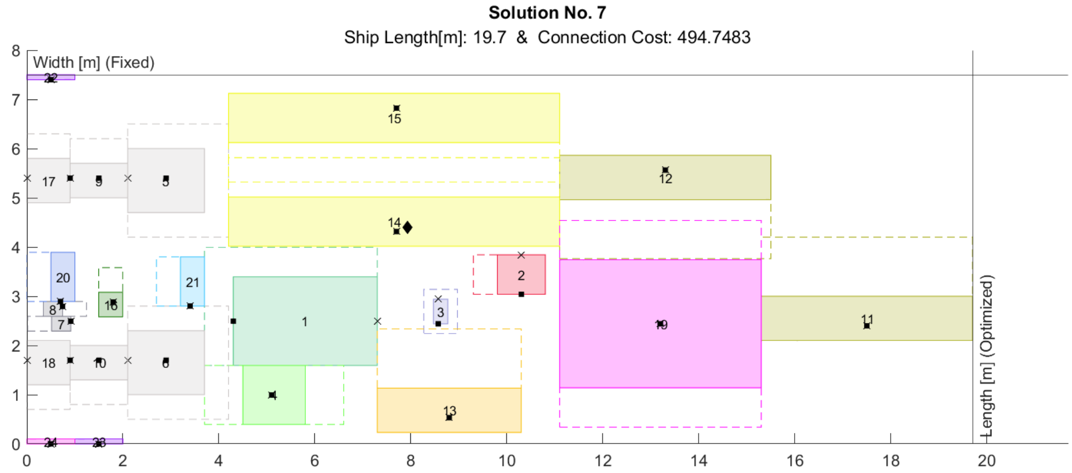


Figure 8.16: Test 2 layout arrangement with the lowest total connection cost $(TCC = 494.7)$

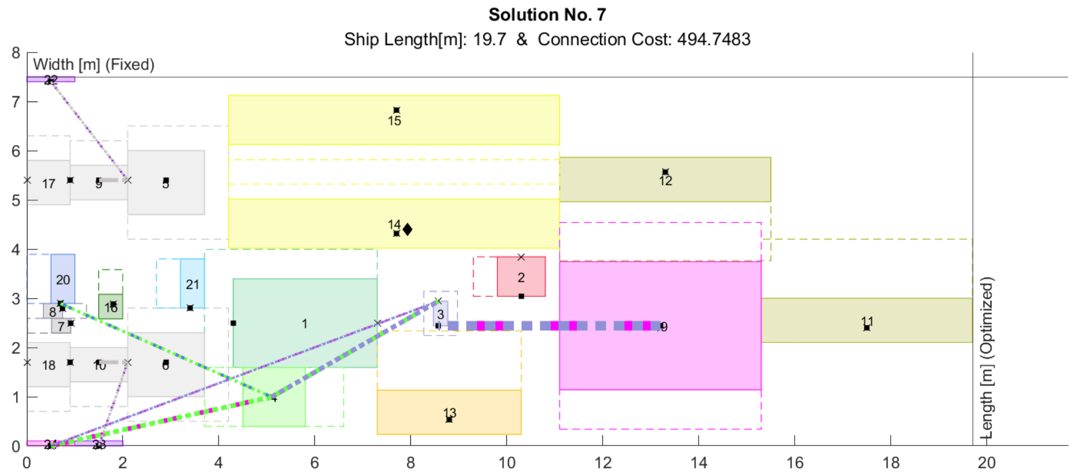


Figure 8.17: Test 2 layout arrangement with the lowest total connection cost including major connections $(TCC = 494.7)$

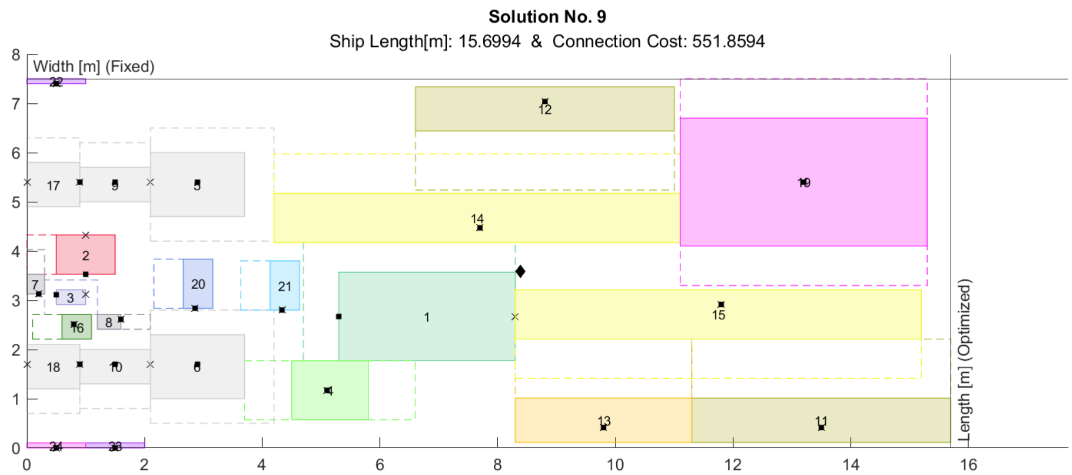


Figure 8.18: Test 2 layout arrangement with the lowest engine room length $(Length = 15.7m)$

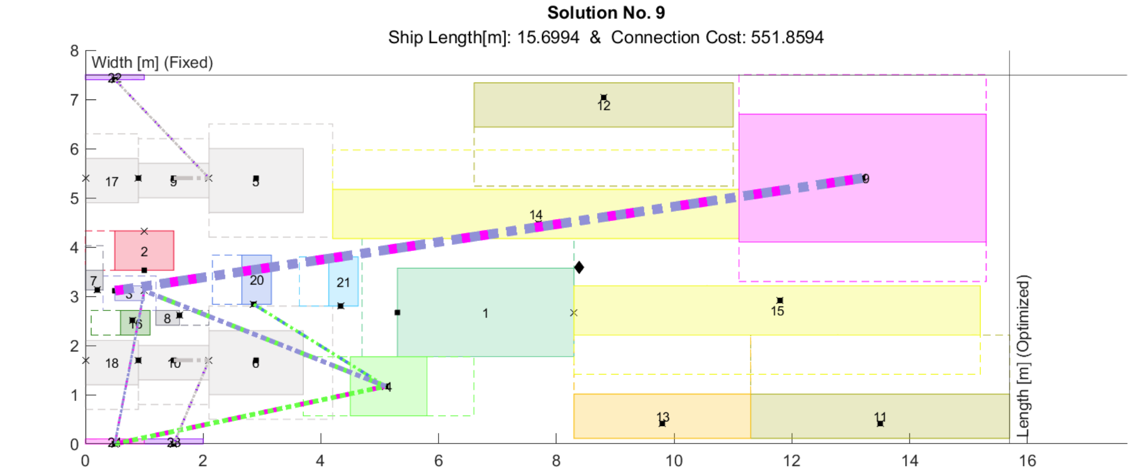
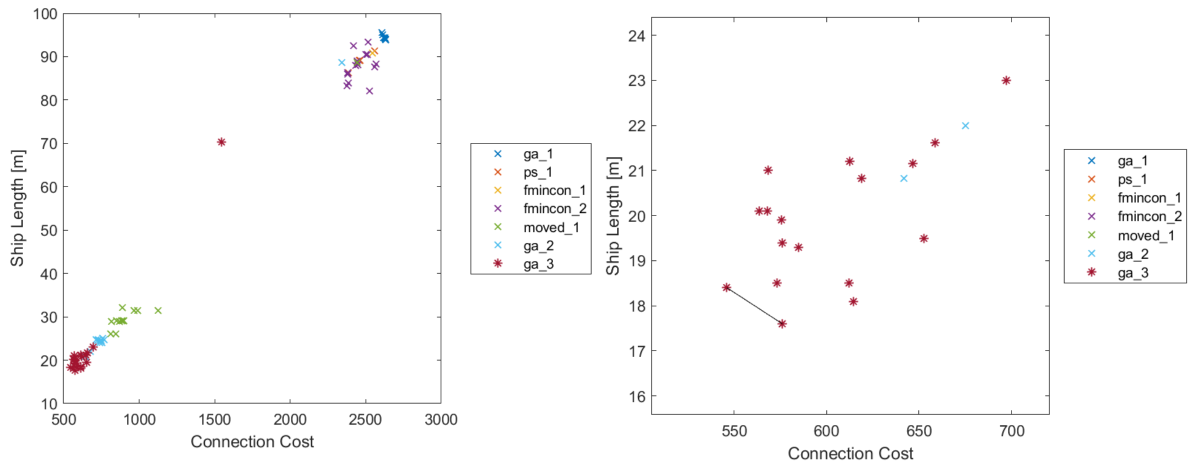


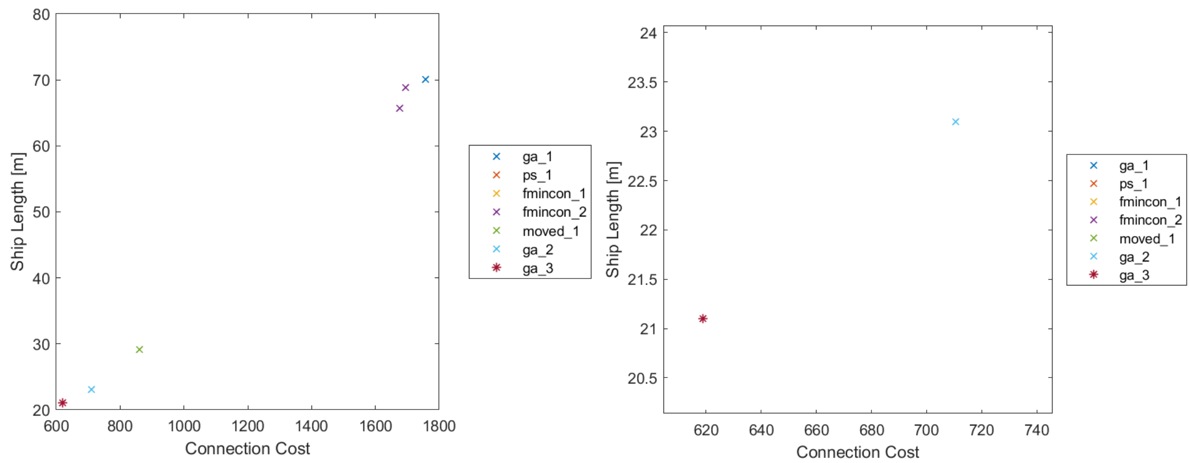
Figure 8.19: Test 2 layout arrangement with the lowest engine room length including major connections $(Length = 15.7m)$



(a) All feasible PPE system solutions in one plot with both MRs and FCs in series configuration

(b) Pareto Front

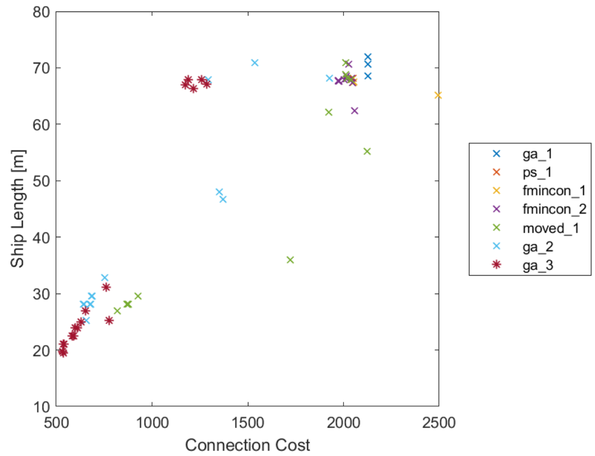
Figure 8.20: All feasible PPE system solutions with both MRs and FCs in series configuration



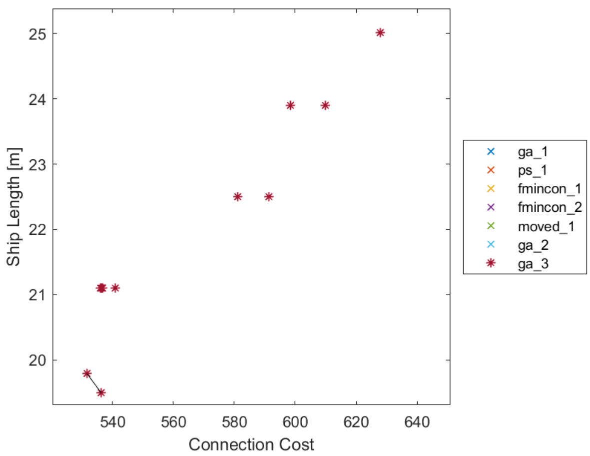
(a) All feasible PPE system solutions in one plot with MRs back to back and FCs in series configuration

(b) Pareto Front

Figure 8.21: All feasible PPE system solutions with MRs back to back and FCs in series configuration

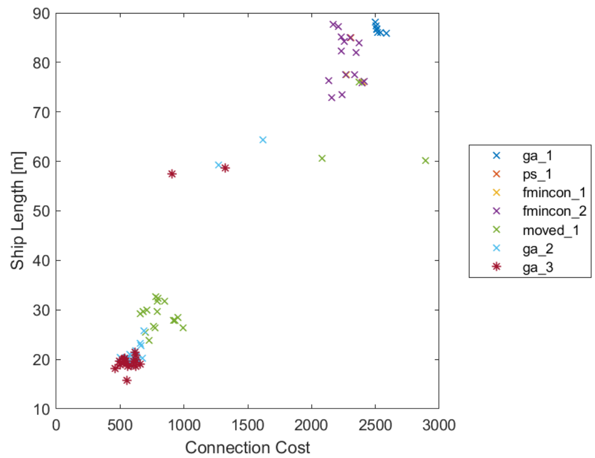


(a) All feasible PPE system solutions in one plot with MRs in series and FCs in back to back configuration

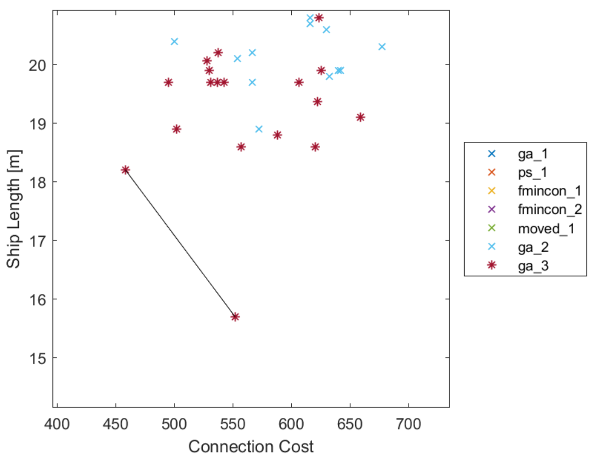


(b) Pareto Front

Figure 8.22: All feasible PPE system solutions with MRs in series and FCs in back to back configuration



(a) All feasible PPE system solutions in one plot with both MRs and FCs in back to back configuration



(b) Pareto Front

Figure 8.23: All feasible PPE system solutions with both MRs and FCs in back to back configuration

8.3.5. Test 3: Transverse Rotational Constraint on BGs

In Test 3 all long PPE system BGs which are consisted of the 2 batteries, the 2 DC switchboards and the AC switchboard have been restricted on the transversely direction. The test 3 is performed to investigate the effect these rotational restrictions can have on the actual engine room length and the connection cost. In reality, in most case scenarios the long and narrow building groups are transversely restricted within the engine room mostly for installation practicalities. Usually they are aligned in the same direction(transversely) as the bulkheads (where already the connections are going up and extending across). Additionally, the side shells of the ship are slightly curved and positioning BGs on the longitudinal direction attached to the ship's walls is not feasible. However, the curved nature of the ship's side wall has already been taken into consideration when choosing the fixed ship's width. The fixed width engine room dimension has been reduced from the initial stage of the design tool to account for this curvature.

Test 3 was performed on the layout configuration where both MRs or FCs are positioned back to back so they did not need to be restricted transversely. This configuration was chosen as it has been found to be the most optimum in terms of both connection cost and ship length.

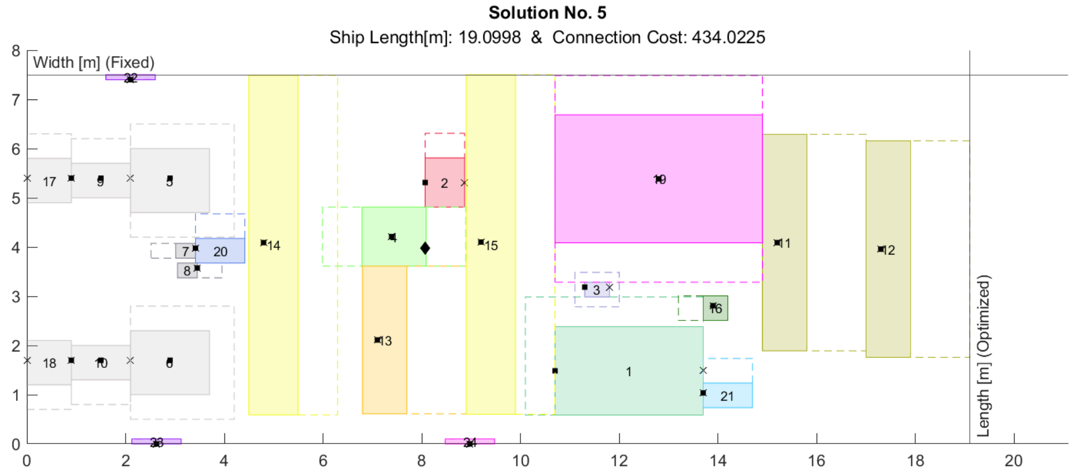


Figure 8.24: PPE system layout with the lowest total connection cost $(TCC = 434.0)$

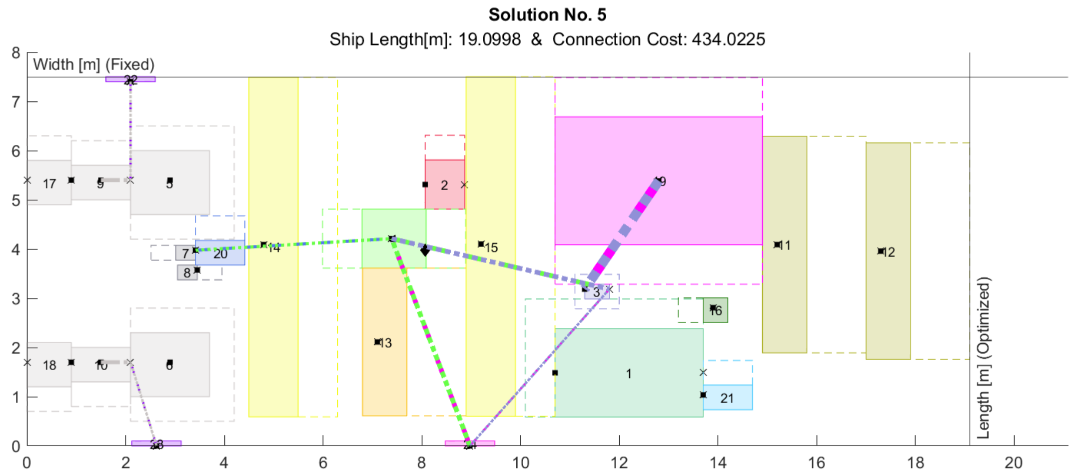


Figure 8.25: PPE system layout with lowest total connection connection including major connections $(TCC = 434.0)$

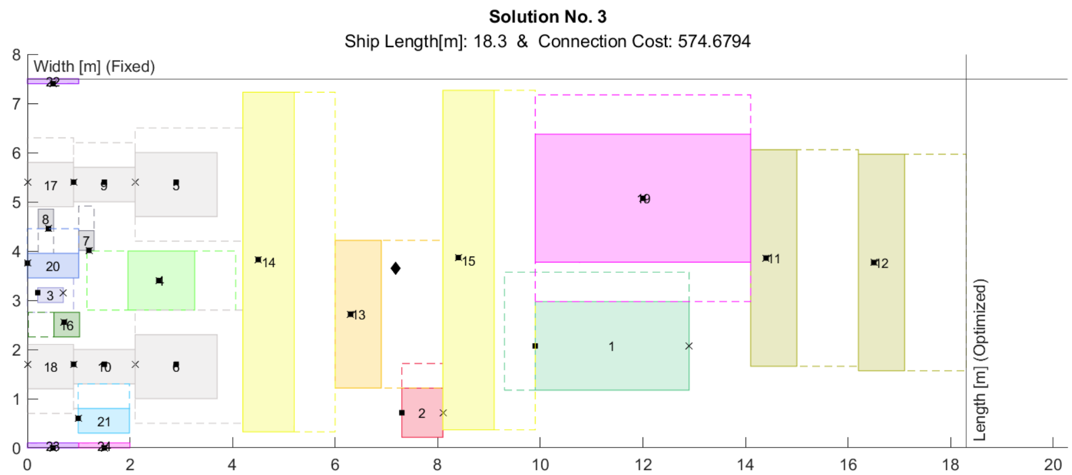


Figure 8.26: PPE system layout with lowest engine room length $(Length = 18.3m)$

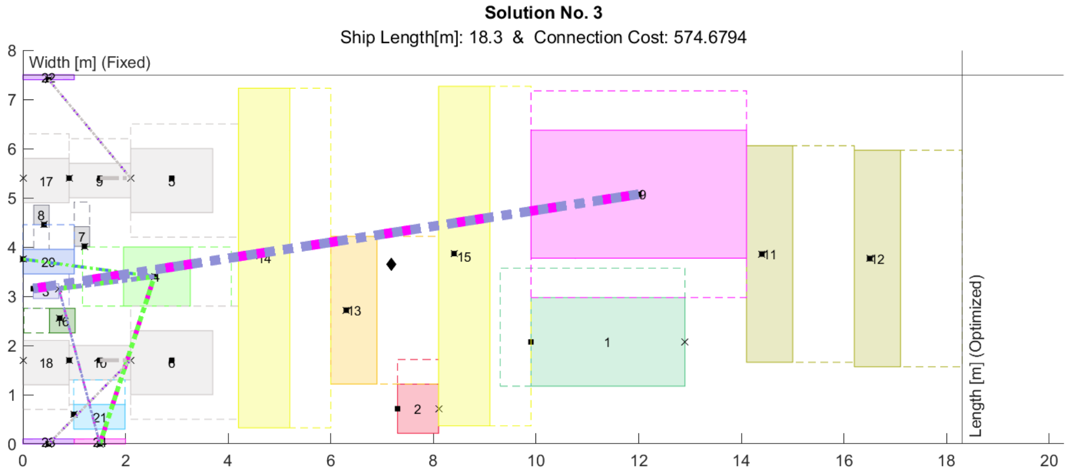


Figure 8.27: PPE system layout with the lowest engine room length including major connections $(Length = 18.3m)$

The generated PPE system layout in figure 8.24 achieved the lowest total connection cost $(TCC = 434.0)$. A further decrease in the total connection cost has been achieved when the long and narrow BGs are restricted transversely. However, when implementing the transverse restriction the layout with the most optimized engine room is worse. This is clearly seen in figure 8.26, the layout with the lowest overall engine room length $(Length = 18.3m)$ with the transverse restriction.

8.3.6. Conclusions

Based on the results and the generated layouts from the Tests 1-3 where connection weight factor has been applied, few important design insights can be concluded:

- Grouping BGs of the same family, result to decreased chaotic nature of layouts, further improve overall engine room's length and the total connection cost.
- Both MRs and FCs generate better layouts in terms of length and connection cost when grouped back to back in a square formation and not side to side in series.
- The lowest and most optimized engine room's length is achieved when relatively small BGs such as the hydrogen supply and the nitrogen tank are situated in the empty spaces near the main engines, exploiting the unused space.
- The lowest and most optimized engine room's length is achieved when all long and narrow BGs are positioned longitudinally across the engine room.
- Transversely constraining long and slender BGs can further decrease total connection costs and the chaotic layout effects but at the expense of a higher engine room length.
- The lowest and most optimized total connection cost is achieved when all long and narrow BGs are positioned transversely across the engine room.

8.4. Actual Connection Matrix

In this section, the CM values in the connection matrix represent the *actual* costs (€/ m). Therefore, now the second objective, the minimum connection cost can be represented in €. The actual costs values used and the equivalent matrix can be seen in table 8.7 and figure 8.28 respectively. The actual costs are deemed to account for materials as well as labour and are best estimates made in discussion with MARIN. In these tests, only the square grouped BGs of methanol reformers (MRs) and fuel cells (FCs) have been implemented as these configuration are found to generate the best layouts. Tests were performed on both constraining and not constraining the long and narrow BGs. Additionally, the grouping of parallel connections that further decrease the actual costs, as specified in sub-section 8.3.3 was taken in consideration. A factor of 1.5 was implemented for the two FCs parallel connections and a factor of 2 was implemented for the four MRs parallel connections. This can be clearly depicted from the actual connection cost matrix 8.28.

Table 8.7: Actual Connection Costs List (€/ m) .

Connection Actual Cost [€/m]	
AC Power Cable	150
DC Power Cable	150
Cathode Exhaust (H_2O) Piping	350
Low Temp. H2O Piping	350
Medium Temp. H2O Piping	350
Raw H2O Piping	350
Fresh H2O Piping	350
Ignition Fuel Piping	725
N2 Piping	725
Diesel Piping	725
Anode Exhaust (H2) Piping	1000
Engine Exhaust	1100
Fuel Piping	1450
Hydrogen Supply	2000
Mechanical Shaft	6250

i Component - Output \ *j Component - Input*	Methanol Fuel Preparation	Diesel Day Supply	Hydrogen Supply	Fuel Cells	Main Engine (1)	Main Engine (2)	ESM Converter (1)	ESM Converter (2)	ESM Machine (1)	ESM Machine (2)	DC distribution (1)	DC distribution (2)	AC distribution (1)	Battery (1)	Battery (2)	Nitrogen Tank	Mechanical Transmission (1)	Mechanical Transmission (2)	Methanol Reformers	Central Cooling Water	Fresh Water Tank	Exhaust Exit (1)	Exhaust Exit (2)	H2 Open Deck Exit
Methanol Fuel Preparation		0	0	0	1450	1450	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel Day Supply	725		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hydrogen Supply	0	0		3000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2000
Fuel Cells	525	0	0		0	0	0	0	0	0	225	225	0	0	0	0	0	0	0	525	0	0	0	3000
Main Engine (1)	0	0	0	0		0	0	0	6250	0	0	0	0	0	0	0	0	0	0	350	0	1100	0	0
Main Engine (2)	0	0	0	0	0		0	0	0	6250	0	0	0	0	0	0	0	0	0	350	0	0	1100	0
ESM Converter (1)	0	0	0	0	0	0		0	150	0	0	0	0	0	0	0	0	0	0	350	0	0	0	0
ESM Converter (2)	0	0	0	0	0	0	0		0	150	0	0	0	0	0	0	0	0	0	350	0	0	0	0
ESM Machine (1)	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	6250	0	0	350	0	0	0	0
ESM Machine (2)	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	6250	0	350	0	0	0	0
DC distribution (1)	0	0	0	0	0	0	150	0	0	0		150	150	150	0	0	0	0	0	0	0	0	0	0
DC distribution (2)	0	0	0	0	0	0	0	150	0	0	150		150	0	150	0	0	0	0	0	0	0	0	0
AC distribution (1)	150	150	0	225	0	0	0	0	150	150	0	0		0	0	0	0	0	0	0	0	0	0	0
Battery (1)	0	0	0	0	0	0	0	0	0	0	150	0	0		0	0	0	0	0	350	0	0	0	0
Battery (2)	0	0	0	0	0	0	0	0	0	0	0	150	0	0		0	0	0	0	350	0	0	0	0
Nitrogen Tank	0	0	725	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
Mechanical Transmission (1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0
Mechanical Transmission (2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0
Methanol Reformers	0	0	4000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0
Central Cooling Water	0	0	0	0	350	350	0	0	350	350	0	0	0	350	350	0	0	0	0		0	0	0	0
Fresh Water Tank	350	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0
Exhaust Exit (1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
Exhaust Exit (2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
H2 Open Deck Exit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Figure 8.28: Actual Connection Cost Matrix (€/ m).

In figure 8.29, the generated PPE system layout with the best actual total cost of 97222 € is presented. In figure 8.30 the generated PPE system layout with the lowest engine room's length of $17.9m$ is shown. In Appendix B.2 many layouts are presented.

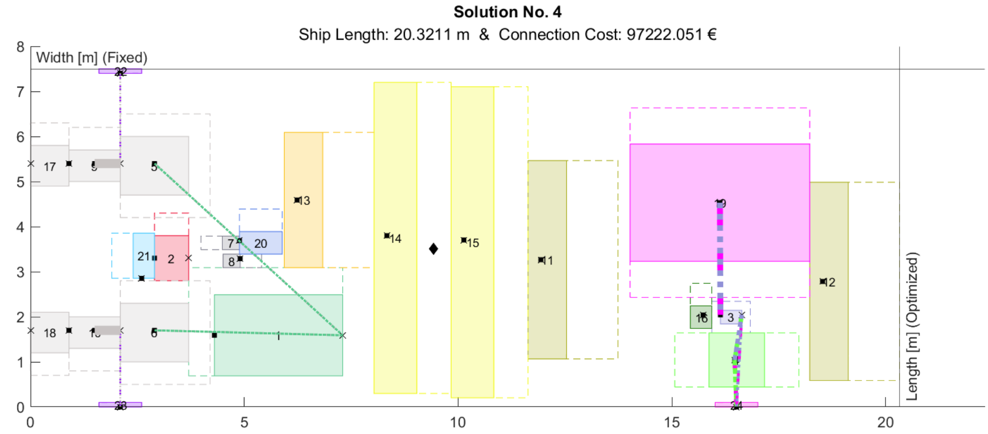


Figure 8.29: PPE system generated layout with the lowest actual total connection cost $(ATCC = 97222€)$

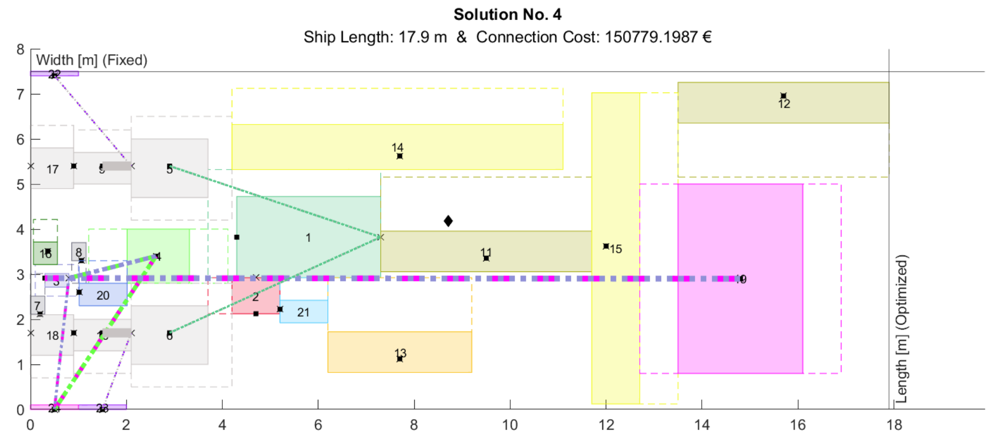
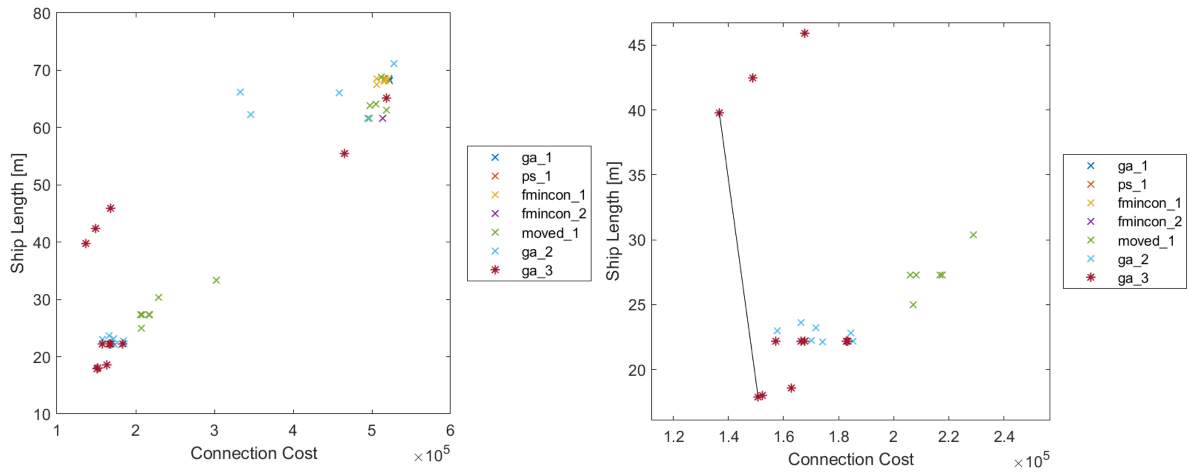


Figure 8.30: PPE system layout with the lowest overall engine room length $Length = 17.9m$

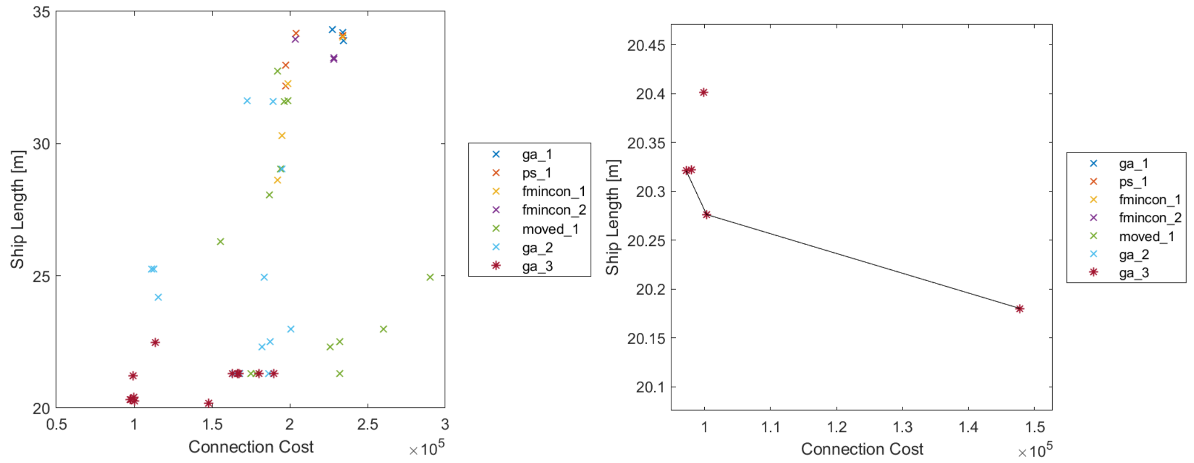
When observing the PPE system layout in figure 8.30 it is clear that by manually moving the FCs and the hydrogen supply to the unused space next to the AC switchboard, the connection cost can be improved significantly without affecting the overall engine room's length. The pareto figures of the actual connection tests are presented in figures 8.31 and 8.32.



(a) All feasible PPE system solutions in one plot with no transverse constraints

(b) Pareto Front

Figure 8.31: All feasible PPE system solutions with no transverse constraints



(a) All feasible PPE system solutions in one plot with transverse constraints

(b) Pareto Front

Figure 8.32: All feasible PPE system solutions with transverse constraints

8.4.1. Conclusions

Based on the generated layouts from the actual costs tests, few important design insights can be concluded:

- It is clear that the connection cost is significantly decreased when all BGs with hydrogen piping as situated nearby as seen in 8.29. The hydrogen piping of the MRs to the hydrogen supply has clearly the greatest effect on the total actual connection cost. A significant difference of about 53500 €is identified between the layouts 8.29 and 8.30.
- Following the same conclusions from the previous tests, the most optimized PPE system layouts in terms of connection are generated when the long and narrow BGs are transversely constrained.
- Following the same conclusions from the previous tests, the most optimized PPE system layouts in terms of total length are generated when the long and narrow BGs are *not* transversely constrained.

8.5. Relationship Matrix

In this part of the report the PPE system layouts based only on the rationale of ship designers is tested. The test has been performed with long and narrow BGs being transversely constrained within the engine room. In this section the relationship between different BGs has been examined in discussions with MARIN and are incorporated with a defined relationship matrix (RM_{ij}) weight factor. These tests do not investigate the generation of the PPE system layouts based on the actual physical connection which has been the case until now, but the relationship between the different BGs. The defined symmetrical matrix presented in figure 8.33 is formulated based on the (RM_{ij}) values depicted in table 8.8.

Table 8.8: Assigned matrix weights based on the BGs relationships

Relationship Matrix (RM_{ij})	
0	*undesirable* for BGs i and j to be close together
0	*unimportant* for BGs i and j to be close together
100	*ordinary* for BGs i and j to be close together
250	*important* for BGs i and j to be close together
1000	*especially important* for BGs i and j to be close together
2000	*absolutely necessary* for BGs i and j to be close together

		j Component - Input																						
i Component - Output		Methanol Fuel Preparation	Diesel Day Supply	Hydrogen Supply	Fuel Cells	Main Engine (1)	Main Engine (2)	ESM Converter (1)	ESM Converter (2)	ESM Machine (1)	ESM Machine (2)	DC distribution (1)	DC distribution (2)	AC distribution	Battery (1)	Battery (2)	Nitrogen Tank	Mechanical Transmission (1)	Mechanical Transmission (2)	Methanol Reformers	Central Cooling Water	Fresh Water Tank	Exhaust Exit (1)	Exhaust Exit (2)	H2 Open Deck Exit
	Methanol Fuel Preparation		250	0	0	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Diesel Day Supply	250		0	0	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Hydrogen Supply	0	0		2000	0	0	0	0	0	0	0	0	0	0	0	2000	0	0	2000	0	0	0	0	2000
	Fuel Cells	0	0	2000		0	0	0	0	0	0	0	0	0	0	0	2000	0	0	2000	0	0	0	0	2000
	Main Engine (1)	100	100	0	0		100	0	0	100	0	0	0	0	0	0	0	100	0	0	0	0	2000	0	0
	Main Engine (2)	100	100	0	0	100		0	0	0	100	0	0	0	0	0	0	0	100	0	0	0	0	2000	0
	ESM Converter (1)	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	ESM Converter (2)	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	ESM Machine (1)	0	0	0	0	100	0	0	0		0	0	0	0	0	0	0	100	0	0	0	0	0	0	0
	ESM Machine (2)	0	0	0	0	0	100	0	0	0		0	0	0	0	0	0	1	100	0	0	0	0	0	0
	DC distribution (1)	0	0	0	0	0	0	1000	1000	0	0		1000	1000	1000	1000	0	0	0	0	0	0	0	0	0
	DC distribution (2)	0	0	0	0	0	0	1000	1000	0	0	1000		1000	1000	1000	0	0	0	0	0	0	0	0	0
	AC distribution	0	0	0	0	0	0	1000	1000	0	0	1000	1000		1000	1000	0	0	0	0	0	0	0	0	0
	Battery (1)	0	0	0	0	0	0	1000	1000	0	0	1000	1000	1000		1000	0	0	0	0	0	0	0	0	0
	Battery (2)	0	0	0	0	0	0	1000	1000	0	0	1000	1000	1000	1000		0	0	0	0	0	0	0	0	0
	Nitrogen Tank	0	0	2000	2000	0	0	0	0	0	0	0	0	0	0	0		0	0	2000	0	0	0	0	0
	Mechanical Transmission (1)	0	0	0	0	100	0	0	0	100	0	0	0	0	0	0	0		0	0	0	0	0	0	0
	Mechanical Transmission (2)	0	0	0	0	0	100	0	0	0	100	0	0	0	0	0	0	0		0	0	0	0	0	0
	Methanol Reformers	0	0	2000	2000	0	0	0	0	0	0	0	0	0	0	0	2000	0	0		0	0	0	0	0
	Central Cooling Water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0
	Fresh Water Tank	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0
	Exhaust Exit (1)	0	0	0	0	2000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
	Exhaust Exit (2)	0	0	0	0	0	2000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
	H2 Open Deck Exit	0	0	2000	2000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Figure 8.33: Defined Relationship Matrix

As discussed in section 8.3.3, the design tool treats all BGs equally and positions them as closely packed as possible. The undesirable effect of not placing two BGs nearby has not been investigated in the previous sections. For the undesirable BGs that are presented with an orange key colour on matrix 8.33, partial positional constraint has been applied. As already discussed in section 8.3.3 the partial/fully constraints can act as a measure of (pseudo)creating compartments within an engine room. It can be similar to having certain dedicated spaces for some BGs.

When designing the use case PPE system, looking from the ship designers' rationale it has been found highly *undesirable* to place nearby some main BGs. For instance, the hydrogen supply cannot be positioned nearby the Main Engines. In reality due to the low auto-ignition temperatures of hydrogen, the hydrogen supply should be avoided to be placed nearby hot surfaces such as the main engines and exhaust piping. Additionally, at the same time the batteries should not be positioned nearby the hydrogen tank or the MEs. Therefore, for these BGs a RM weight value of 0 has been assigned between them and they have been partially constrained across the engine room. The main engines have been fully constrained at the aft of the engine room, the batteries partially constrained in the middle section and the hydrogen supply BG partially constrained in the front section of the engine room. This positional enforcement was applied to ensure that these BGs are not located nearby.

On the other hand, the hydrogen supply, the fuel cells, the nitrogen tank, the hydrogen interface and the methanol reformer reformers are interconnected with a RM weight value of 2000. These five building groups have been grouped as *absolutely necessary* to be located nearby. These BGs are essential to be nearby to each when looking from the rationale point of view again for safety reasons, limiting long hydrogen connections across the engine room. The enforcement of positionally constraining the hydrogen supply together with the implementation of these high RM weight values between these BGs will hopefully enforce their arrangement in the front section of the engine room. Moreover, when designing a PPE system, is common to arrange all electrical components nearby. Therefore, the AC and DC distribution and the batteries BGs have been assigned with an RM weight value of 1000 as they are *especially important* to be close together.

Figures 8.34 and 8.35 illustrate the most optimized layout configuration in terms of connection cost.

Figures 8.36 and 8.37 are the PPE system configuration that achieved the lowest engine room's length. Numerous PPE system generated layouts are presented in Appendix B.3.

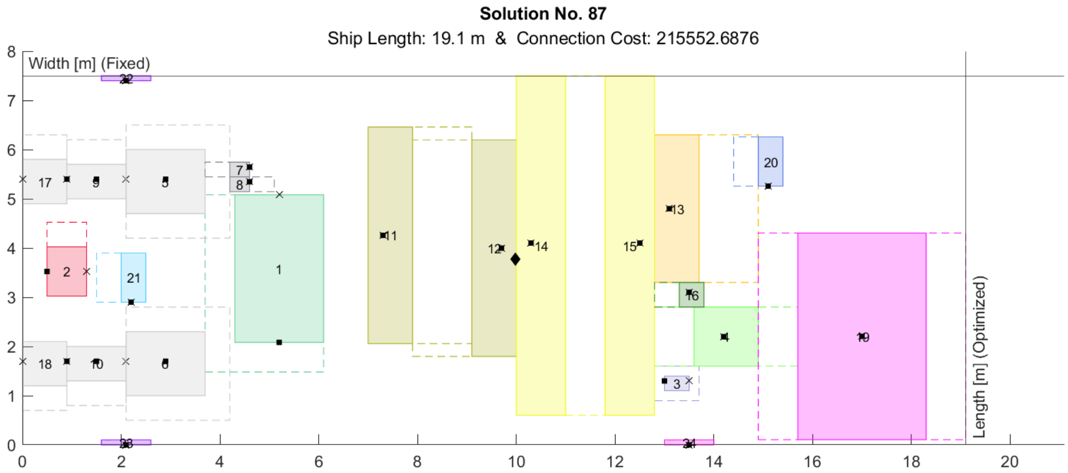


Figure 8.34: PPE system layout with the lowest connection cost

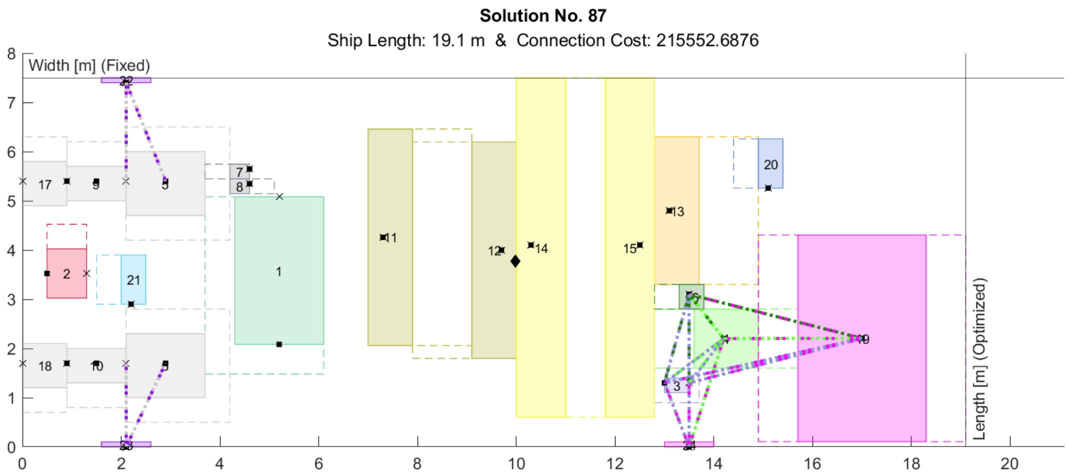


Figure 8.35: PPE system layout with the lowest connection cost including all major relationship connections $RM \geq 2000$

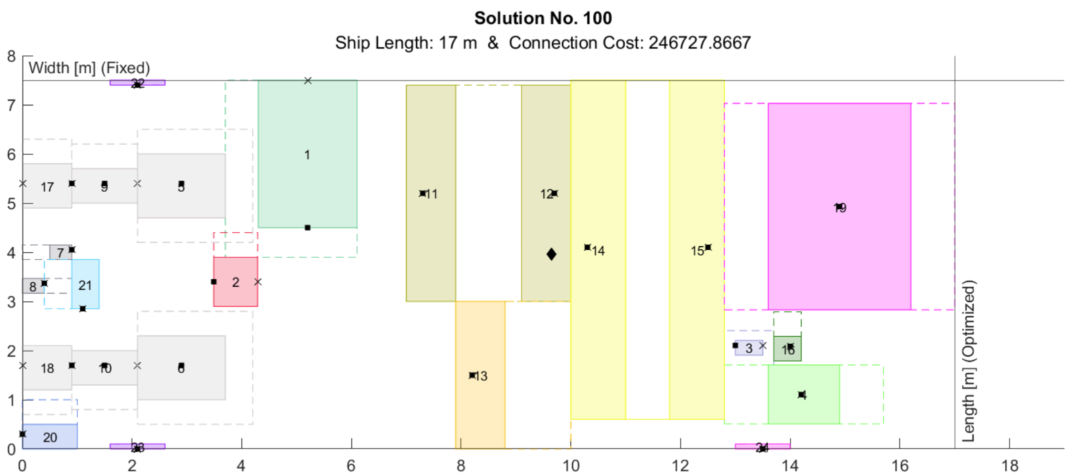


Figure 8.36: PPE system layout with the lowest engine room's length

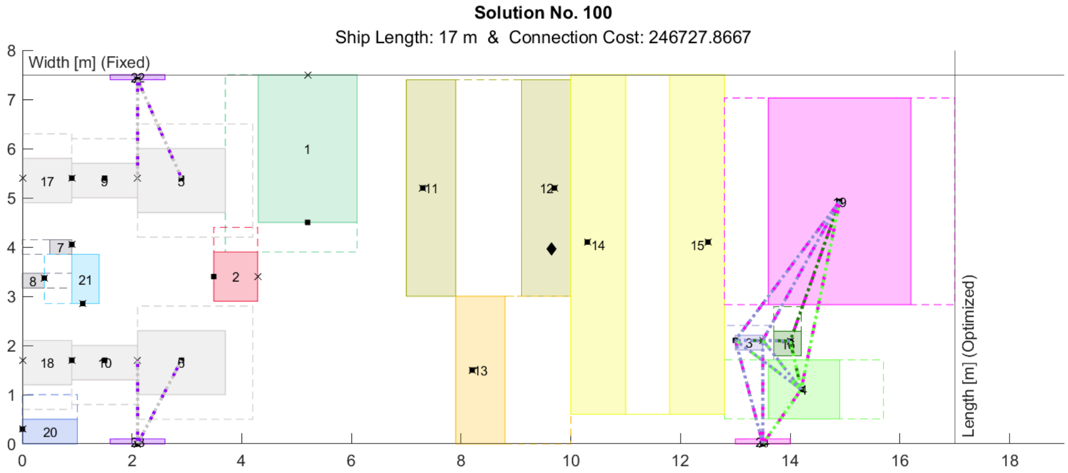


Figure 8.37: PPE system layout with the lowest engine room's length including all major relationship connections $RM \geq 2000$

8.5.1. Conclusions

- Constraining some critical BGs and simultaneously enforcing strong relationships groups using the RM_{ij} values, the design tool generates more organized PPE system arrangement layouts.
- Enforcing important BGs for the reasons discussed earlier such as the hydrogen supply and the batteries in specific regions across the engine room, guides the design tool to successfully subdivide the PPE system. As clearly seen from the figures above all electrical BGs are situated within the centre of the engine room and all hydrogen related BGs are located at the back. The engine room can therefore be subdivided manually in three different compartments.
- However, as clearly depicted from the figures when enforcing certain BGs and further constraining the solution exploration space of the design tool, a large space within the engine room remains unused.

9
Design Tool Discussion

Numerous tests have been performed, several PPE systems have been generated and various design insights have been obtained. In this chapter the design tool exact connection with the MBSE methodology is elaborated. Moreover, a baseline layout is used for comparison with the obtained PPE system results and the influence of input changes is tested. The tool limitations are discussed and validation of design tool is performed. Research sub-question **5** is addressed.

9.1. Design Tool and MBSE methodology

The design tool successfully generates initial General Arrangement Plans (GAPs) of novel PPE systems. It acts as an add-on working complementary with the MBSE methodology and more specifically with the physical architecture. All necessary inputs with regard to the BGs and their connections specifics are obtained from the MBSE environment established within the physical architecture. Before having the ability to compose in detail the physical architecture, the MBSE environment captures all essential details starting in the exploration phase with the operational analysis and system analysis. Within the operational and system analysis the user needs and their structure is explored in a focused systems overview.

Operational Architecture

From a high level perspective in the MBSE operational analysis, all operational capabilities and their associated operational activities are documented. These are appropriately defined in discussions between the ship designers, the clients and the stakeholders. For instance, the operational capabilities can include the vessel's maximum speed, maximum endurance, vessel's autonomy in nautical miles, the vessels sea state operational capabilities, the required emission reductions and many more. The activities associated with these capabilities can include the provision of propulsion power, auxiliary power, emergency services etc. Moreover, within the operational analysis the boundary of the 'system' that is modelled is carefully defined, indicating which activities will be included in the PPE system and which not. For instance, the hull and propulsor detailed specifics can be chosen to be outside boundaries of the novel PPE system and therefore not within the scope of the study.

System Architecture

In the next level of architecture, the system analysis, the systems performing the defined activities are determined and the boundary around the system are set, defining the external interfaces. In this level of architecture detailed studies are performed incorporating Power Time Characteristics (PTCs) that capture the properties of the power consumption in time for the propulsion and auxiliary categories and are manually synthesised, using measured data and experiences from past projects. After defining these power specifics SPEC tool is used to explore and identify the most suitable PPE system as explained in section 4.1.2.

Logical and Physical Architecture

The logical architecture follows the system analysis. The functions attributed to the system in the system architecture are transitioned to logical functions without a further layer of detail. In the logical architecture the architecture is organized without making technological considerations or implementation choices. That is done at the Physical Architecture level. In the physical architecture the exact physical BGs solutions are assigned that are used by the design tool. For instance, the logical architecture can contain the component ‘Fuel Storage’ and in the physical architecture the exact physical type of fuel and its storage is selected. This has been identified through the SPEC tool analysis.

Design Tool

Following the physical architecture the design tool captures these physical solutions of the PPE system’s BGs and their interactions. This enables the transition from schematic model diagrams that capture all PPE system’s physical properties within the MBSE environment to the actual General Arrangement Plans (GAPs). The generated tools can be then implemented within the MBSE environment in the physical architecture to further enhance the initial discussions during the conceptual stage. The visualizations generated and the provision of the spatial arrangement guidance of the BGs and their interactions enable ship designers to further understand geometrically the system. For instance, an approximate of the required engine room length is provided, the configuration of the same family of BGs (eg Methanol Reformers) can be chosen to be in positioned back to back instead of in series. Additionally, long and narrow BGs can be chosen not to be transversely constrained as further reductions in length are observed to be achieved etc.

9.2. Baseline Layout Comparison

The design tool generates novel PPE system layouts using numerous data obtained from the MBSE physical architecture as inputs. These novel PPE system layouts created by the design tool have not been previously investigated and their spatial configuration cannot be directly compared to previous similar designs. This is a complexity challenge presented when designing novel PPE systems for Zero Emission Ships (ZESs) and has been previously addressed within the report. As no prior designs for this specific novel PPE system are available to be used for comparison, in this section a baseline layout has been manually created. This layout presented in figure 9.1, is compared with the generated PPE system layouts generated throughout the various types of tests, in sections 8.3 - 8.5. The clear objective comparison is presented in table 9.1. The table with all the BGs is presented in an earlier section, in figure 8.15.

The baseline PPE system layout is designed based upon some important design drivers:

- Separate Compartment for batteries, hydrogen-related BGs and Main Engines (MEs).
- Batteries, hydrogen-related BGs and MEs compartments should not be positioned next to each other.
- Fuel tanks should be separated from the MEs for fire integrity.
- All long and slender BGs are transversely constrained. This includes the batteries and the DC switchboards.
- Centre of Gravity (CoG) must be located near the ship’s centerline.

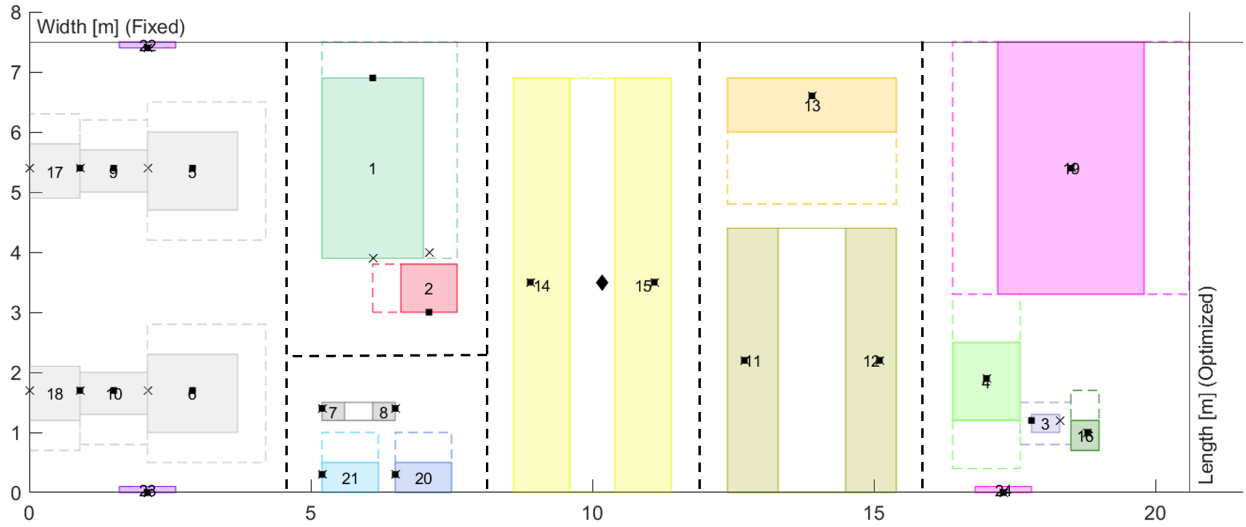


Figure 9.1: Baseline Comparison Layout. The dotted lines present the possible separation of different engine room compartments.

In table 9.1 the baseline layout is presented with its equivalent length ($20.6m$) and the three different types of total connection cost objective values. This baseline PPE system layout is compared against the best layouts with the most optimized length from each test type. Their equivalent total connection cost is provided. Additionally, the baseline layout is compared with the layouts that have obtained the most optimized total connection cost value from each test type. Their corresponding length values are presented as well.

Table 9.1: Comparison Results with Baseline Layout. Green and Red key colours used to represent the improved or worse objective value respectively. In brackets the percentage reduction/increase is highlighted.

		Total Connection Cost		
	Length [m]	Relative Connection Weight Factor	Actual Cost Factor [€]	Relationship Factor
Baseline Comparison Layout	**20.6**	**500.4**	**111463.8**	**253355.7**
Connection Weight Matrix (Length)	15.7 (23.8%)	551.9 (10.3%)		
Connection Weight Matrix (T. Con. Cost)	19.1 (7.3%)	434 (13.3%)		
Actual Connection Matrix (Length)	17.9 (13.1%)		150779.2 (35.3%)	
Actual Connection Matrix (T. Con. Cost)	20.3 (1.5%)		97222.1 (12.8%)	
Relationship Matrix (Length)	17 (17.5%)			246727.9 (2.6%)
Relationship Matrix (T. Con. Cost)	19.1 (7.3%)			215552.7 (14.9%)

When comparing the baseline layout with the two layouts that have generated the most optimized length and total connection cost respectively for each test type, the design tool generated GAPs with improved objective values. In all three test types reductions for both objectives have been achieved when compared with the baseline layout. All PPE system GAPs presented in the table have outperformed the baseline layout in terms of the length objective with maximum reductions up to 23.8% and an engine room length of 15.7m (refer to figure 8.18). Additionally, improvements are noticed in all the different types of total connection cost objective. For instance, observing the actual connection matrix test a reduction of about 13% has been achieved which leads to a reduction of about 14000 € in total connection costs (refer to figure 8.29).

9.3. Influence of Input uncertainties

As clearly explained in section 8.3.1, all Building Group (BG) dimensions and their defined margins used for all the tests are carefully chosen based on actual industry data, rules and regulations or careful discussions within MARIN. These are the input data that generate the PPE system General Arrangement Plans (GAPs) presented in the previous sections.

As these layouts are generated during the conceptual design stage and given the juvenile nature of some of these systems, any defined input estimate can be susceptible to change. Therefore, in this section, the potential influence in sizing changes on the defined input estimates is tested. A quick study where the sizing estimates are altered is performed. The uncertainty tests were performed using the actual connection matrix and using the same set tests performed in section 8.4. With these set of tests the effect on the actual total connection cost in terms of € can be compared.

Two different type of uncertainty studies were conducted. In the first study, all BG margins within the PPE system have been increased by 20%. In the second study, all BGs actual dimensions have been increased by 20%. This was achieved by increasing only the length or only the width of each BG. Table 9.2 presents the obtained results.

	Original Tests	**20% increased margin area**	**20% increased BG area**
Mean Actual Total Connection Cost [€]	147787.9	179817.7	159677.3
Mean Optimized Length [m]	20.7	21.6	22.9
Best Actual Total Connection Cost [€]	97222.1 (T)	109090.8 (T)	124511.7
Best Optimized Length [m]	17.9	16.9	19.1

Figure 9.2: Uncertainty study results. (T) is used to represent that the best GAP was obtained with long and narrow BGs being transversely constrained across the engine room

As seen in the table, the increased area size in margins or BG dimensions affects the results generated. As expected, when comparing with the original tests performed in section 8.4, the mean values of both actual total connection cost and optimized length are increased.

Investigating in more detail the actual total connection cost, a larger mean increase is observed with the increase in BG margins (32029.8 €/ increase per PPE system layout) when compared with the actual BG dimensions increase (11889.4 €/ increase per PPE system layout). This is justified by the fact that most BGs have defined clearance spaces in more than one side all around and therefore their increase in most cases directly impacts the distance between BGs. On the other hand, increasing a BG's actual dimension was performed by changing only one dimension side and without altering the position of I/O gates. Therefore, when the tool appropriately rotates a BG in some cases the connection cost is not affected. For instance, if a connection input/output point is located at the edge/boundary of a BG, altering the width or length will not affect the I/O point location, which will still be located at the BG's edge. Unless they are located within the BG, many input/output points remained unaffected and therefore a less significant increase in the mean actual total connection cost is observed with the increased BG area. Concluding, increasing the BGs dimensions makes their rotational orientation determined by the tool more important when looking at the total connection cost objective. Therefore, the relative small increase in the mean total connection cost when increasing BG dimensions by 20% reveals that the tool successfully rotates the BGs to minimize as much as possible this objective.

Additionally, when looking at the mean optimized length, a larger mean length increase is observed when increasing the BGs area. A mean increase of 0.9m and 2.2m is observed when increasing the BGs margins and the BGs dimensions respectively. This effect is justified as the optimized length objective, entirely depends on the total BG area coverage of the PPE system within the engine room. The margins area as defined within the tool can be overlapped whereas the actual BG area cannot and therefore the negative impact in optimizing the length for the increased BG dimensions is greater.

The best layouts in terms of connection cost and length for both uncertainty studies are provided below. The best layouts in terms of the two objectives of the original tests can be seen in figures 8.29 and 8.30. Is noteworthy to mention that in a test with 20% increased margins the tool generated one PPE system GAP with even more optimized than the original tests conducted prior. This can be seen in figure 9.4.

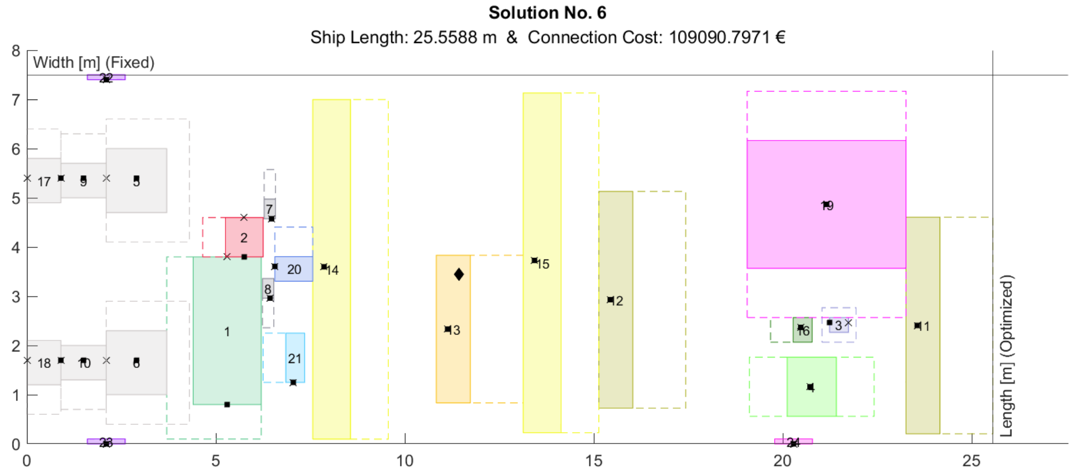


Figure 9.3: Most optimized actual total connection cost PPE system GAP with increased BG margin area (20%)

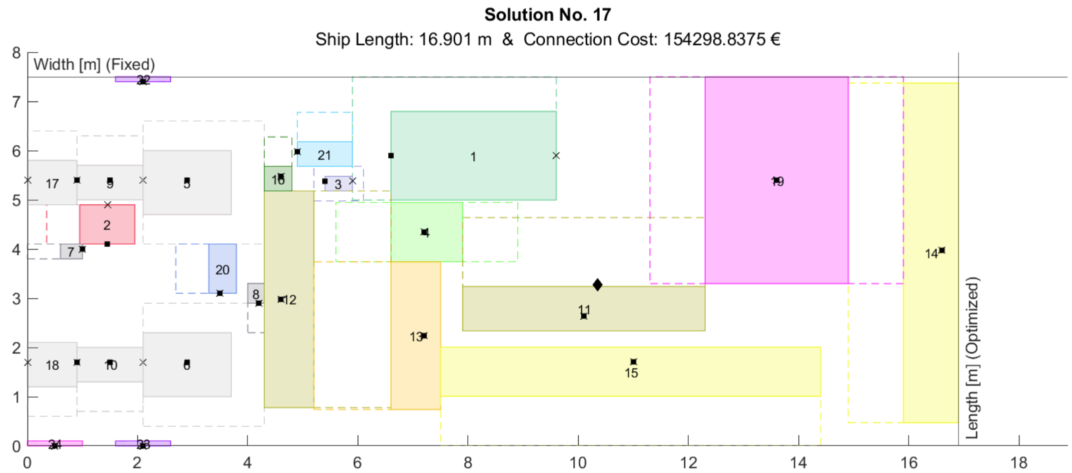


Figure 9.4: Most optimized total length PPE system GAP with increased margin area (20%)

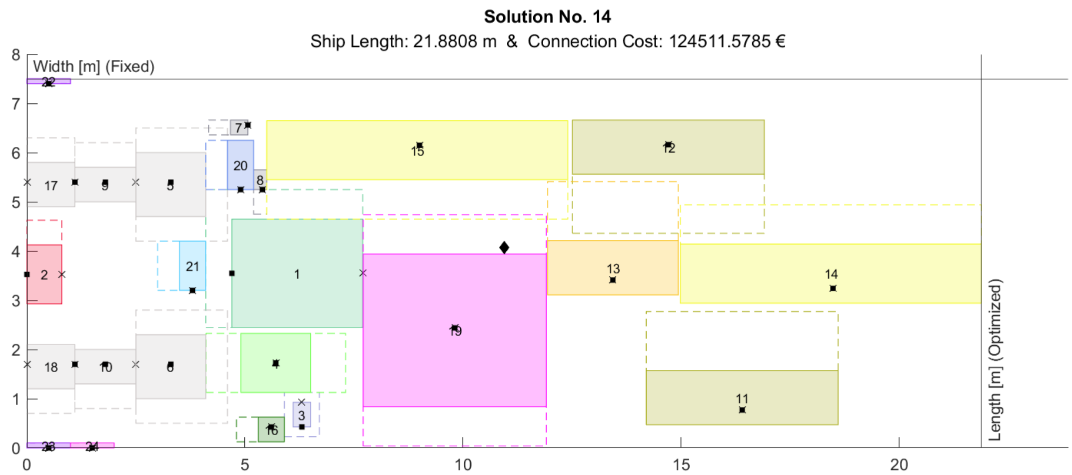


Figure 9.5: Most optimized actual total connection cost PPE system GAP with increased BG area (20%)

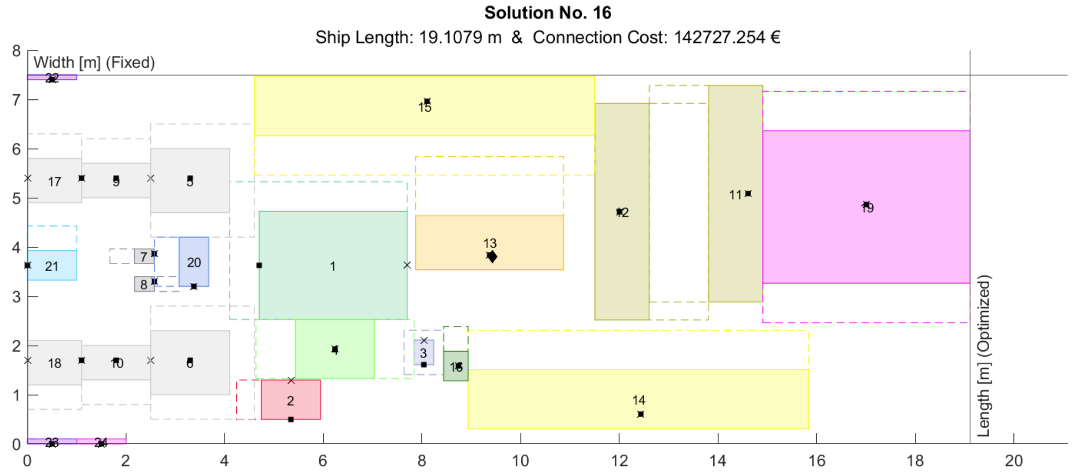


Figure 9.6: Most optimized total length PPE system GAP with increased BG area (20%)

9.4. Design tool Limitations

After performing numerous tests the design tool has some clear limitations. These are discussed in detail in the following subsections. The limitations are broken down into two categories; expected and unexpected.

Expected Limitations

9.4.1. Grouping and Rotations

The design tool does not have the capability to automatically group BGs of the same family in different configurations. For the testing of the different FCs and MRs configurations it was necessary to perform several tests of the different possible configuration combinations, manually altered within the excel file.

Additionally, as explained earlier in the report the tool only handles a 90 degree counterclockwise rotation. This can be very limiting for BGs with uneven surrounding clearance spaces and different tests were manually performed. For instance, different tests were performed to account for the electrical BGs initially facing in the same direction and different tests performed were the have an initial opposite orientation. Both limitations discussed in this subsection, highly increased the number of tests that were needed to be performed.

9.4.2. Pathing

The current design tool does not account for pathing routes across the engine room. For instance, layout in figure 8.36 makes pathing access longitudinally across the engine room infeasible. Higher clearance spaces around the BGs could have been implemented to account for pathing. However, this would have led to less realistic PPE system configurations. A vital insight of the design tool is to initially explore how much area and consequently how much engine room's length should be allocated for the novel PPE system on board a specific use case with predefined dimensions. Assigning more clearance spaces for all BGs to account for pathing routes, would have resulted in a more vague and uncertain engine room's length requirement insight. The aim of the current design tool is to initially explore the novel PPE layouts and with some manual alterations by the ship designers rationale and logic to further enhance the layouts.

9.4.3. Actual connection cost

Is important to note that for the actual connection cost even that the connections have been modelled using the Manhattan distance measurement, the reality in 3-dimensional differs and the model connections are simplified. There are some configurations that inherently have a higher connection cost than others and the design model successfully minimizes. However, it is not a detailed connectivity cost. In reality connections span across with a height differences as shown Figure 7.4b. The actual 3D routing leads to higher connection costs than are not accounted for in the model's 2D layouts.

Unexpected Limitations

9.4.4. Decision Variable Notation

Deciding on the formulation of the decision variables can be very important for the design tool performance. The required runtime, the quality and the variety of the solutions highly depend on the initial defined decision variables. As previously explained the decision variables formulation that is used in this report design tool are implemented based on another master's thesis. The corresponding decision variable notation holds all variables in long arrays. For each BG, three elements are necessary to hold all the information, one for the current x-coordinate, one for the current y-coordinate and one for the rotation. Therefore, a PPE system model with 24 BGs will have all decision variables stored within a design vector formulated by an array with 72 elements. In section 7.1.3 the decision notation was described in detail. The current notation supports all possible layouts, including a ton of inefficient and invalid (due to the defined constraints) layouts.

The Genetic Algorithm uses the selected solutions (and some non-selected solutions to keep variety) to produce the new population. Two solutions are required and are used as parents to create a new solution during the crossover process. With the current decision variables and the defined constraints, the first GA is having a hard time in improving solutions because each decision variable represents a different feature (xpos, ypos and rotation) of a different BG. Since each decision variable (gene) represents a different BG and since the objectives are highly nonlinear, it is hard for dominant genes to create better layouts. It is even hard to produce layouts that do not violate constraints.

Moreover, the new population generated are also mutated in each generation. Mutation is used in GA where one or more decision variable is changed randomly, without using the parents, to provide diverse solutions. In the way the decision variables are defined in the current design tool, taking a valid layout and change a few decision variables randomly, it is highly probable that the new generated solution with the new mutated gene is invalid because is violating the defined constraints and the mutated BGs overlap.

It is possible to use some other more simplified decision variable logic. For example, if every object had the same dimensions, a coordinate names could be assigned for each square, just like a chess board, and the decision variables could be the coordinate names like "B7". This would decrease the run-time duration a lot since GA could simply flip the locations of two objects. However, it would not be possible to use different sized objects or rotations with this decision variable notation.

A different decision variable notation that was investigated and can be used in known as bay structure approach, implemented by Lee et al. [92]. The total rectangular space can be sub-divided into several bays of varying width according to the largest width of the BG. Each facility with unequal-area and fixed shape is then placed in the bay one by one, from left to right.

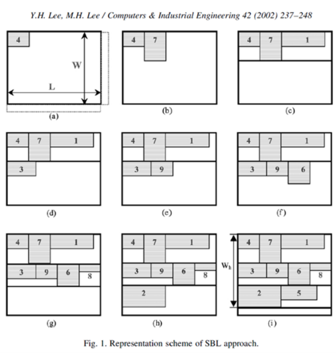


Figure 9.7: Bay structure approach [117]

9.4.5. Difficulty in rearranging small-sized BGs

It can be seen from the generated layouts that the small-sized BGs are found to be ”trapped” in between large sized BGs. This is caused due to the implementation of the fixer code that solves the unused space problem of the first GA, where all BGs are forced to move as much as possible to the left of the engine room. After the fixer code is being implemented, is difficult for the 2nd and 3rd GA in most cases to make the small-size BGs to move across the engine room as large BGs occupy most of the nearby space and are therefore trapped. This can be clearly seen in several layouts were the hydrogen supply is situated far away from the methanol reformers BG even though their connection is highly important. As seen in the last test with the relationship matrix when constraining these small BGs for the first time the issue can be easily solved. Additionally, the ship designers can manually make minor changes after investigating the PPE system arrangement layouts.

However, a possible solution to this negative effect that can be investigated is the gradual development and generation of the PPE layouts broken down in two stages. Firstly, in the first stage the design tool can be developed to arrange only the large BGs within the engine room area. This would enable the large-sized BGs to be arranged in a more optimum layout without the interference of the small-sized BGs. Then in the second part of the design tool, the smaller sized BGs can be gradually added one by one in the optimization process. For instance, this order can be based on the importance of the small BGs based on their degree in and out and their total connection cost to other BGs.

9.5. Validation

In this section validation on the design tool is conducted. Validation is the process of building confidence in its usefulness with respect to a purpose. The usefulness of a design method is associated with whether the method provides design solutions ‘correctly’ known as *effectiveness*, and whether it provides ‘correct’ design solutions, known as *efficiency* [118].

The validation process followed in this thesis is obtained from a validating design method published in a research paper conducted by Pedersen et al. [118]. The validation process is known as the Validation Square and is used to to evaluate both the effectiveness and the efficiency of the design tool the method using qualitative and quantitative measures respectively [118]. This is illustrated in Figure 9.8, where the Validation Square is presented at the bottom, and the process is detailed explained and performed to validate the design tool.

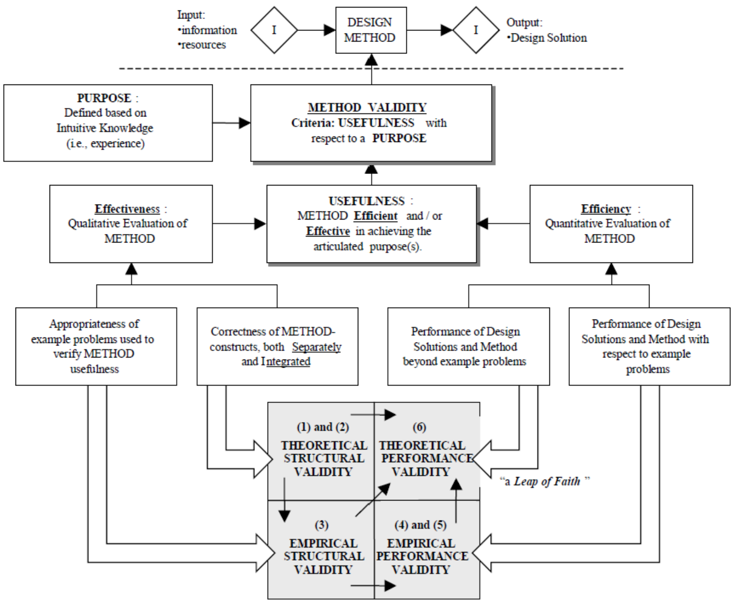


Figure 9.8: Validation Square Process [118]

9.5.1. Structural Validation / A Qualitative Process

The first two boxes within the validation square named *theoretical structural validity* and *empirical structural validity* are concerned with the *qualitative* process and to check the *effectiveness* of the design tool.

For the theoretical structural validity there are two important steps [118].

> *(1) Accepting the construct's validity: In order to build confidence in the validity of the individual constructs constituting the method, we suggest using the literature.*
>
> *(2) Accepting method consistency: Accepting method consistency: In order to build confidence in the way the constructs are put together in the method we suggest using flowchart representations focusing on information flow.*

Both steps (1) and (2) that are concerned with the theoretical structural validity are extensively provided in section 7.2. In this section an appropriate flowchart diagram presenting all the different design tool's algorithms steps and their corresponding literature studies are provided. Additionally, in section 7.1, the defined model optimization structure, the corresponding literature and the design tool's required inputs are explained in detail. Both sections provide all the required information necessary for accepting both the construct's validity and the method consistency.

For the empirical structural validity there is one important step [118].

> *(3) Accepting the example problems: In order to build confidence in the appropriateness of the example problems chosen for verifying the method performance, we suggest documentation in stages. First, document that the example problems are similar to the problems for which the method constructs are generally accepted. Then, document that the example problems represent the actual problem for which the method is intended. Finally, document that the data associated with the example problems can support a conclusion.*

As presented in section 7.3, a small-scale example with 5 facilities is used to present the visualization of the tool. The example shown captured all the necessary inputs in the same way that a PPE system is constructed. The small-scale example captures: the different facilities, their dimensions, their unequal required margins, their exact I/O locations, weight and the connection matrix to represent all facilities connections. Even though this illustrated example is on a small-scale, the complexity needed for its construction for including all the necessary input parameters, is exactly the same as with an actual PPE system with more BGs involved. The design tool has successfully illustrated the ability to generated different alternative layouts based on the two different defined objectives for investigation and trade-off analysis by the ship designers.

9.5.2. Performance Validation / A Quantitative Process

The last two boxes within the validation square named *empirical performance validity* and *theoretical performance validity* are concerned with the *quantitative* process and to check the *efficiency* of the design tool.

For the empirical performance validity there are two important steps [118].

> *(4) Accepting usefulness of method for some example problems: To build confidence in the usefulness of the method, we suggest using representative example problems. In this way, the outcome of the method can be evaluated in terms of its usefulness.*

As presented in chapter 8 several testings on a real large motor yacht use case PPE system have been performed. This case study is a representative example problem of a real PPE system and the usefulness of the tool in generating initial PPE layouts from the MBSE methodology and generating some initial design insights has been evaluated.

> *(5) Accepting that usefulness is linked to applying the method: To build confidence that the usefulness of the resulting example problem solutions is linked to applying the method, we*

> *suggest evaluating the contributions to usefulness from each construct individually. This is done by comparing the solutions with and without the construct, allowing a quantitative evaluation. In addition, solutions should be compared to those found with existing design approaches.*

The developed design tool, generated initial 2D arrangement layouts of a novel PPE system using MBSE physical architecture details. This has not been previously investigated in literature and therefore cannot be compared quantitatively. The generation of layouts investigating the spatial requirements of novel PPE systems developed in the MBSE methodology has not been previously researched.

For the theoretical performance validity there is one important step [118].

> *(6) Accepting usefulness of method beyond example problems*

The easy implementation of different use cases and different PPE systems was considered a highly useful feature. The design tool offers the ability to test different use cases PPE systems with no adjustments on the tool code. By just adjusting an excel spreadsheet file, different vessels' PPE systems layouts can be generated.

10 Conclusions and Recommendations

In this final chapter research conclusions are drawn and future research recommendations are presented.

10.1. Conclusions

The report started by identifying the multifaceted complexity challenges of designing Zero Emission Ships (ZESs) with novel Propulsion Power and Energy (PPE) systems in chapter 1. In chapter 2 the importance of the early ship design stage, the traditional ship design spiral limitations and some advantages of other alternative design approaches have been elaborated. From these two chapters, it was concluded that the traditional ship design approaches cannot solely deal with the increased design complexity faced nowadays and immediate technological progress and innovation within ship design is essential.

Therefore, in chapter 3, a state-of-the-art methodology that can help in addressing the traditional ship design approach limitations, knows as Model Based Systems Engineering methodology has been introduced. A description of the methodology's origin from systems engineering and the advantages it can offer has been described. In chapter 4, the implementation of the MBSE within MARIN and how it currently aids in the exploration and conceptual design of PPE systems together with other design tools like SPEC has been outlined. The research in these chapters described the methodology's benefits and its exact role within MARIN. Moreover, it helped in identifying a gap and formulating the thesis research objective and questions in section 5.1.1.

The formulation of a design tool to work as an add-on with the MBSE physical architecture and SPEC tool for the generation of initial PPE system layouts accommodated within the machinery space has been identified. The design tool developed needed to satisfy numerous defined requirements such as capturing the critical physical properties and interconnections of building groups, generate various arrangement layouts, handle important design arrangement rules.

Research in chapter 6, identified that the best way to model the machinery arrangement problem is the Facility Layout Problem (FLP). This modelling method was considered to be most promising to handle the arrangement of specialized building groups with unique requirements in the ship's engine room. Genetic Algorithm was selected as the main resolution approach together with the FLP as it is a well established and robust algorithm and due to its easy implementation.

In chapter 7, the design tool's methodology and the way it was constructed within MATLAB is described in detail. Additionally, the PPE case study of the large motor yacht has been introduced. Finally, this enabled to illustrate the design tool's usefulness in chapter 8, where several type of tests have been performed.

The design tool effectively generates numerous initial PPE system GAPs that can be further analyzed by ship designers and obtain important design insights that cannot be comprehended by the MBSE physical architecture alone. Several alternative layouts can be compared for trade-off analysis between the two main objectives, optimized length and total connection cost. However, some of these GAPs can be chaotic and not ideal in many instances, but, with minor manual alterations and adjustments they can lead to adequate layouts for further explorations. As presented in section 9.1, the design tool produced GAPs with noticeable improvements on the two objectives when compared with the baseline PPE system GAP. Finally, the design tool has important limitations that are discussed in section 9.4.

Concluding, the thesis was guided by the research questions stated in section 5.1.1. This lead to the above mentioned conclusions. The main research objective has been accomplished as the transition from the MBSE PPE system's physical architecture to the geometrical description and modeling of the actual PPE system has been achieved.

10.2. Recommendations

The literature study in section 3.3 has revealed that only a limited amount of studies have investigated the implementation of the MBSE methodology with ship design efforts. Additionally, from section 6.1, it can be concluded that limited literature exists for the exploration of machinery space design on board vessels. These layouts are manually performed by experienced naval architects and marine engineers, and more research is essential.

The current design tool's performance can be further enhanced and several ways are recommended:

- Develop a way in which pathing routes can be accounted within the engine room.
- Develop an automatic grouping of building groups within the tool. This grouping ideally should handle different grouping configurations.
- Further enhance the rotational ability of BGs with full rotations.
- Implement different step solvers/algorithms that can further improve the final solutions.

Finally, as already discussed, deciding on the formulation of the decision variables can be very important for the design tool performance. The current defined notation supports all possible layouts, including a ton of inefficient and invalid layouts. Different decision variable notations can improve the performance of generating PPE system GAPs as recommended in section 9.4.4.

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A

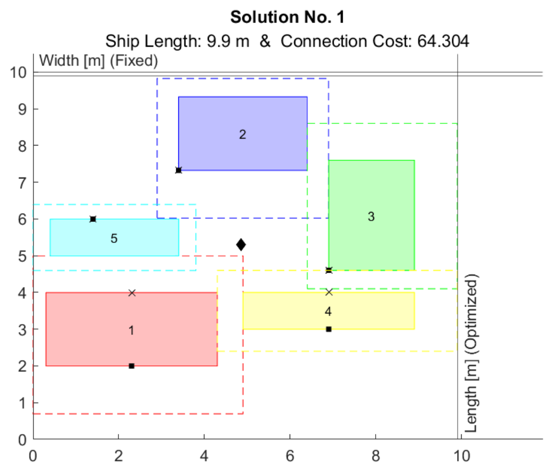
Appendix: Example Model Test

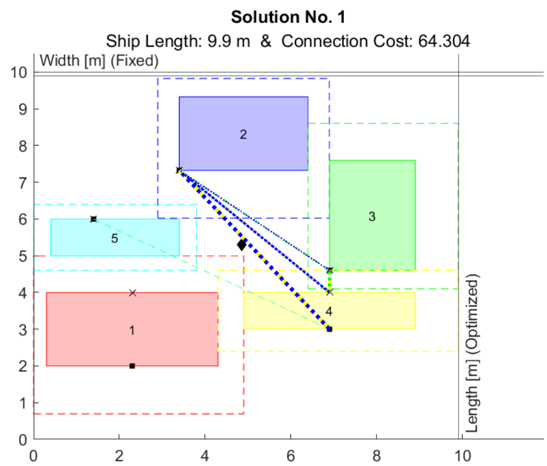
Facilities		Margins [m]				Dimensions [m]		Input/Output Position [m]				Rotational Constraint [0,1]	Positional Constraints [m]				Weights [kg]	Code
Name	Color	Left	Right	Top	Bottom	Widths	Lengths	Inputs X	Outputs X	Inputs Y	Outputs Y	Allowed to Rotate	X Min	Y Min	X Max	Y Max		
Red	Red	0.3	0.6	1	1.3	2	4	2	2	0	2	1	0	0	9.00E+99	9.00E+99	1	1
Blue	Blue	0.5	0.5	0.5	1.3	2	3	0	0	0	0	1	0	0	9.00E+99	9.00E+99	2	2
Green	Green	0.5	1	0.5	1	2	3	0	0	2	2	1	0	0	9.00E+99	9.00E+99	3	3
Yellow	Yellow	0.6	0.6	0.6	1	4	1	0	1	2	2	1	0	0	9.00E+99	9.00E+99	4	4
Cyan	Cyan	0.4	0.4	0.4	0.4	1	3	1	1	1	1	1	0	0	9.00E+99	9.00E+99	5	5

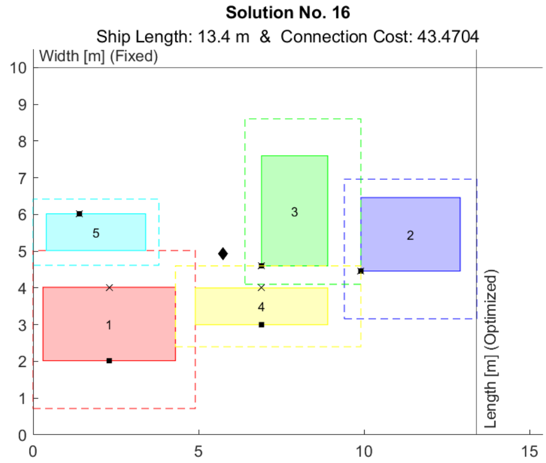
Figure A.1: Small-scale test facilities Input Details

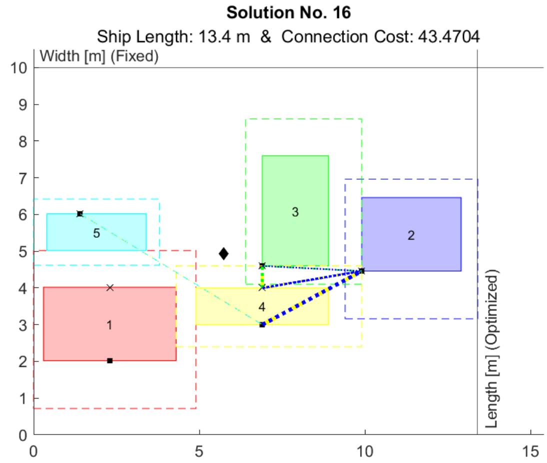
		j Component - Input				
		Red	Blue	Green	Yellow	Cyan
I Component Output	Red	0	0	0	0	0
	Blue	0	0	2	5	0
	Green	0	1	0	0	0
	Yellow	0	3	4	0	0
	Cyan	0	0	0	1	0

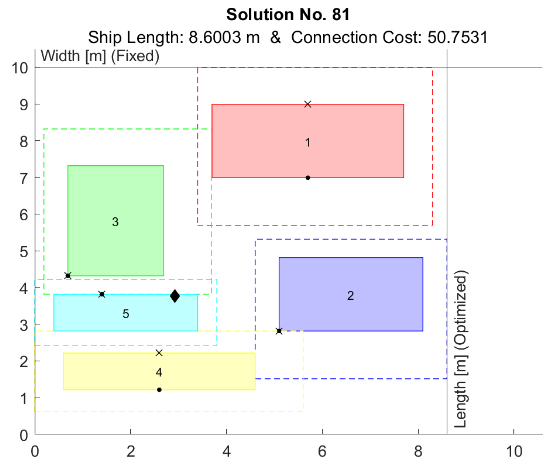
Figure A.2: Small-scale test Connection Matrix

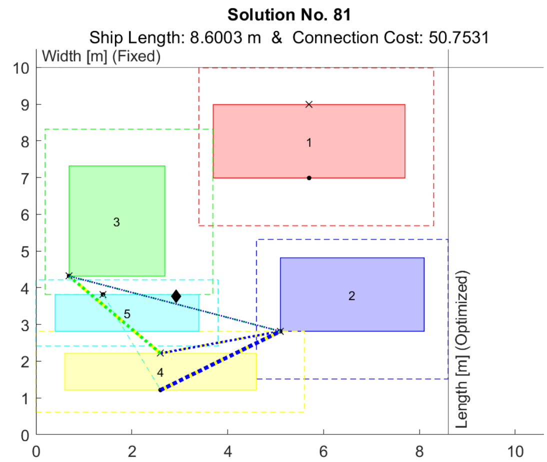


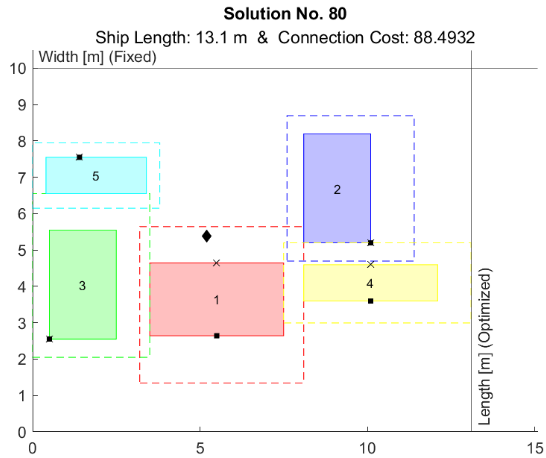


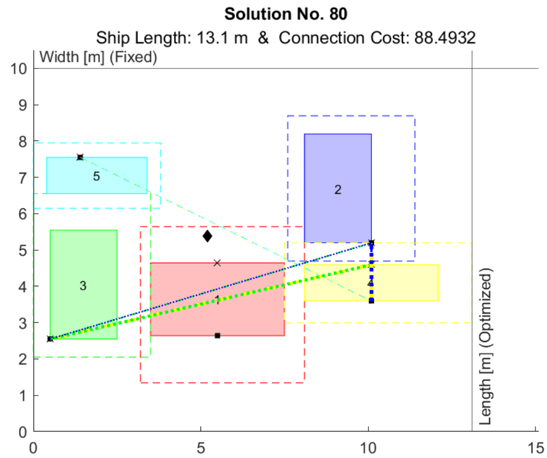

Solution No. 16
Ship Length: 13.4 m & Connection Cost: 43.4704
Width [m] (Fixed)
Length [m] (Optimized)

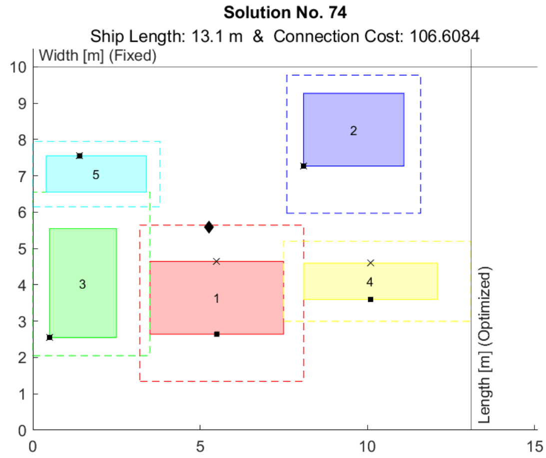

Solution No. 16
Ship Length: 13.4 m & Connection Cost: 43.4704
Width [m] (Fixed)
Length [m] (Optimized)

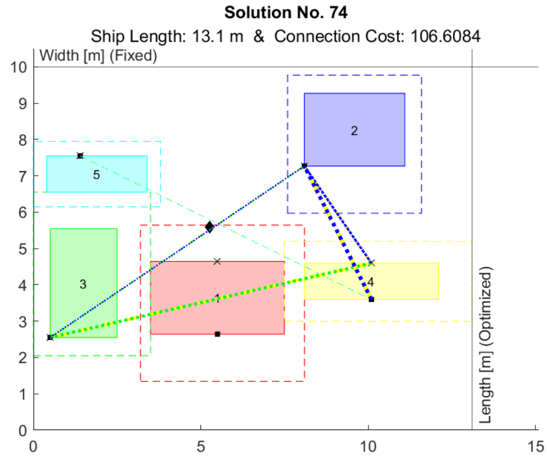

Solution No. 81
Ship Length: 8.6003 m & Connection Cost: 50.7531
Width [m] (Fixed)
Length [m] (Optimized)


Solution No. 81
Ship Length: 8.6003 m & Connection Cost: 50.7531
Width [m] (Fixed)
Length [m] (Optimized)


Solution No. 80
Ship Length: 13.1 m & Connection Cost: 88.4932
Width [m] (Fixed)
Length [m] (Optimized)


Solution No. 80
Ship Length: 13.1 m & Connection Cost: 88.4932
Width [m] (Fixed)
Length [m] (Optimized)


Solution No. 74
Ship Length: 13.1 m & Connection Cost: 106.6084
Width [m] (Fixed)
Length [m] (Optimized)
1
2
3
4
5


Solution No. 74
Ship Length: 13.1 m & Connection Cost: 106.6084
Width [m] (Fixed)
Length [m] (Optimized)
1
2
3
4
5

B

Appendix: Model Tests Results

B.1. Connection Matrix Tests

B.1.1. Test 1 - Initial Test with the 28 defined BGs

	BlockName
1	"Methanol Fuel Preparation"
2	"Diesel Day Supply"
3	"Hydrogen Supply"
4	"Fuel Cell (1)"
5	"Fuel Cell (2)"
6	"Main Engine (1)"
7	"Main Engine (2)"
8	"ESM Converter (1)"
9	"ESM Converter (2)"
10	"ESM Machine (1)"
11	"ESM Machine (2)"
12	"DC Distribution (1)"
13	"DC Distribution (2)"
14	"AC Distribution (1)"
15	"Battery (1)"
16	"Battery (2)"
17	"Nitrogen Tank"
18	"Mechanical Transmission (1)"
19	"Mechanical Transmission (2)"
20	"Methanol Reformer (1)"
21	"Methanol Reformer (2)"
22	"Methanol Reformer (3)"
23	"Methanol Reformer (4)"
24	"Central Cooling Water"
25	"Fresh Water Tank"
26	"Exhaust Interface PS (1)"
27	"Exhaust Interface SS (2)"
28	"H2 Exhaust Interface"

Figure B.1: All Building Groups Layout code names

	order_of_algs	mean_connection_cost	mean_ship_length	number_of_solutions
1	"ga_1"	1.0119e+03	39.1333	3
2	"ps_1"	973.4642	39.6536	6
3	"fmincon_1"	973.4445	39.6436	6
4	"fmincon_2"	973.2588	39.6445	6
5	"moved_1"	745.8467	22.7200	5
6	"ga_2"	581.8285	21.2478	5
7	"ga_3"	543.7544	19.5492	6

Figure B.2: Table showing the improvement in the different algorithms

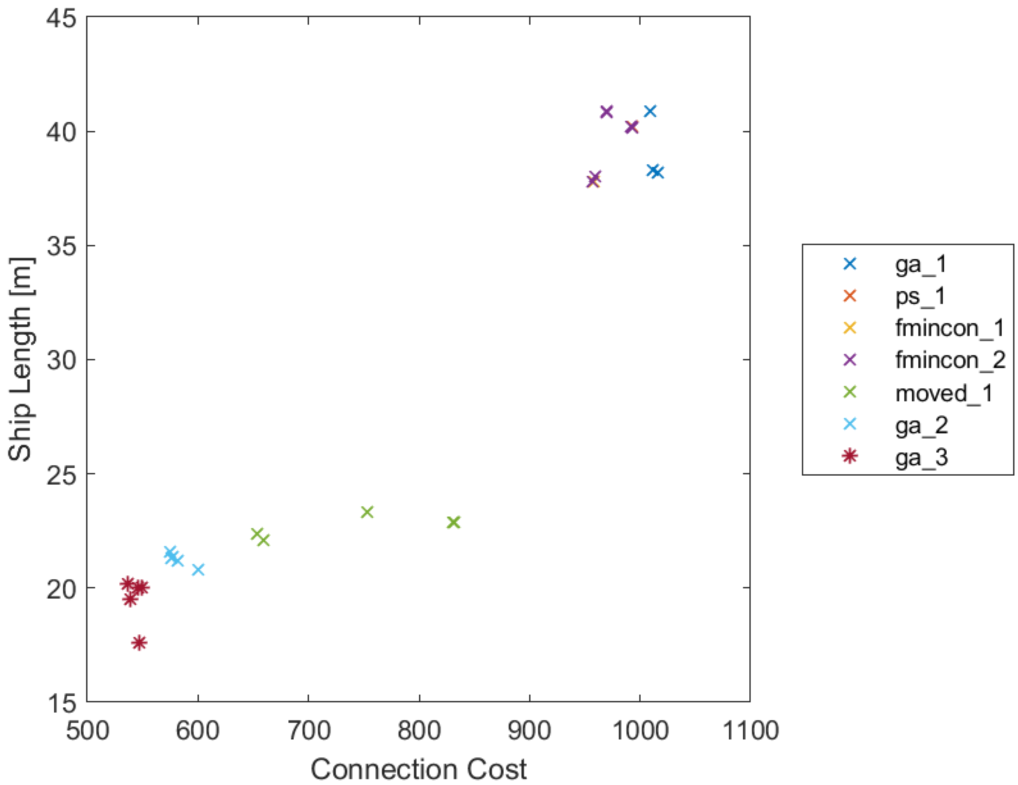
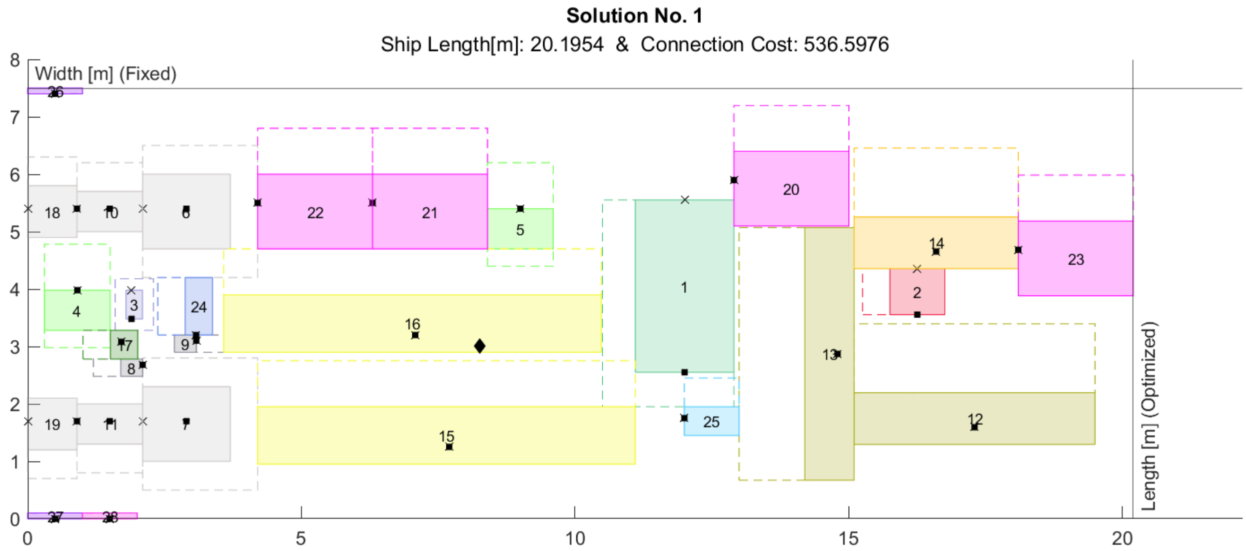


Figure B.3: All solutions in one pareto front

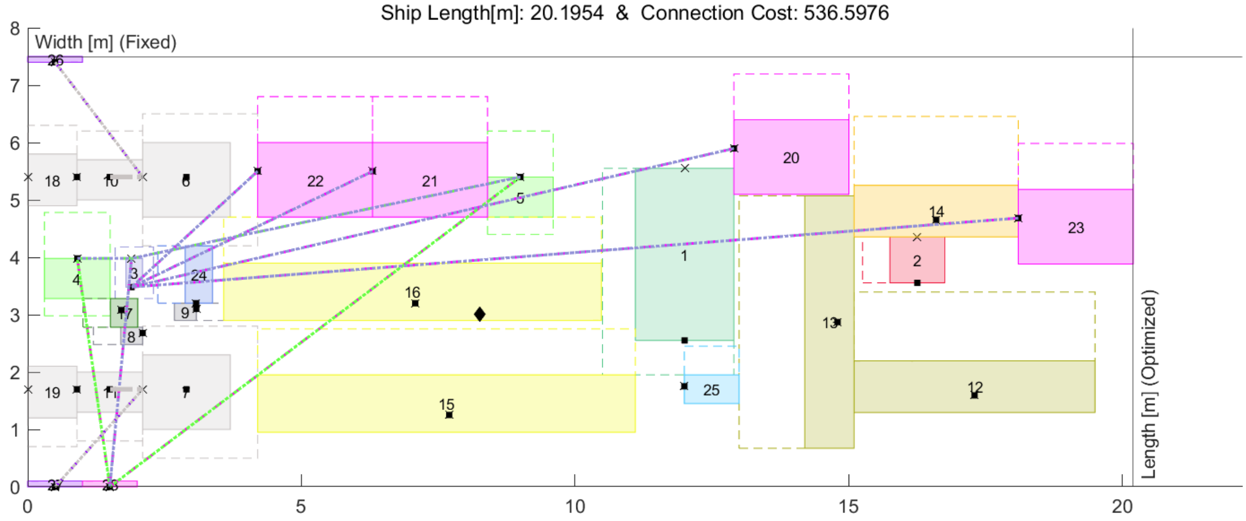
	BlockName	x_position	y_position	is_rotated
1	"Methanol Fuel Preparation"	11.5781	4.3202	1
2	"Diesel Day Supply"	10.1748	4.5202	0
3	"Hydrogen Supply"	1.8000	3.4868	0
4	"Fuel Cell (1)"	0.2684	3.2868	0
5	"Fuel Cell (2)"	2.9906	3.2000	0
6	"Main Engine (1)"	2.1000	4.7000	0
7	"Main Engine (2)"	2.1000	1	0
8	"ESM Converter (1)"	4.2000	5.4965	1
9	"ESM Converter (2)"	3.8723	6.7965	0
10	"ESM Machine (1)"	0.9000	5	0
11	"ESM Machine (2)"	0.9000	1.3000	0
12	"DC Distribution (1)"	16.7020	0.1799	1
13	"DC Distribution (2)"	11.1001	0.1199	0
14	"AC Distribution (1)"	5	4.5202	0
15	"Battery (1)"	4.2000	0.9202	0
16	"Battery (2)"	4.2000	2.7202	0
17	"Nitrogen Tank"	1.4684	2.7868	1
18	"Mechanical Transmission (1)"	0	4.9000	0
19	"Mechanical Transmission (2)"	0	1.2000	0
20	"Methanol Reformer (1)"	13.3781	2.9423	0
21	"Methanol Reformer (2)"	13.3781	5.2257	0
22	"Methanol Reformer (3)"	8	4.5202	0
23	"Methanol Reformer (4)"	11.1000	2.2202	0
24	"Central Cooling Water"	4.2000	5.7965	1
25	"Fresh Water Tank"	1.4953	4	1
26	"Exhaust Interface PS (1)"	0	7.4000	0
27	"Exhaust Interface SS (2)"	0	0	0
28	"H2 Exhaust Interface"	1	0	0
29	" Length: 17.602 Connection Cost: 546.9579 CoG Coordinates: (7.9065, 2.9058)"	NaN	NaN	NaN

Figure B.4: Table showing the exact details for each BG position, the engine room length, the total connection cost and the exact CoG coordinates. This table corresponds to solution number 3 shown below. Added to show what the design tool can generate.



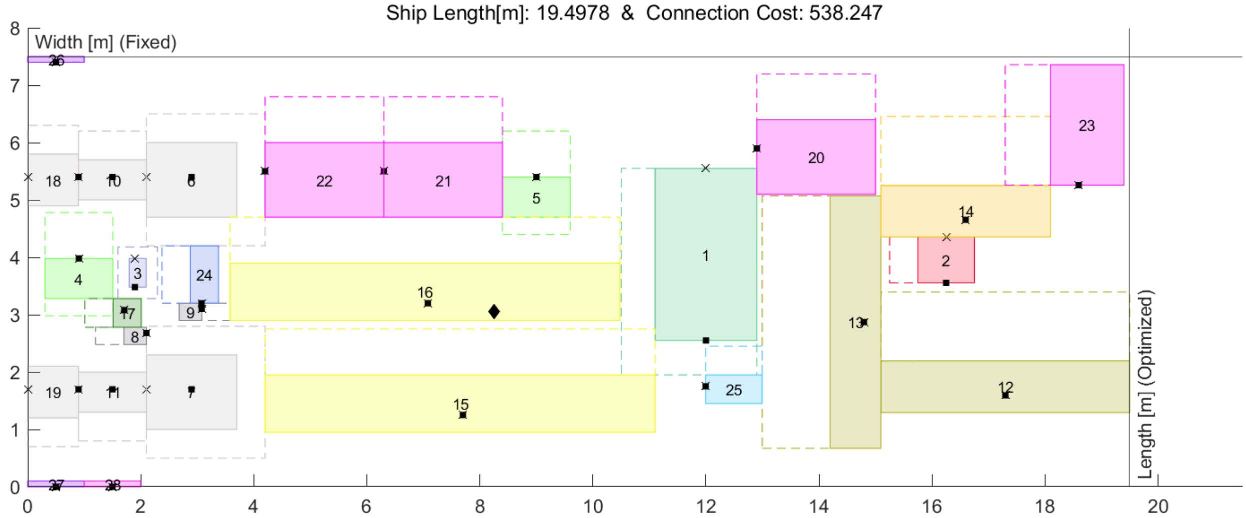
Solution No. 1

Ship Length[m]: 20.1954 & Connection Cost: 536.5976



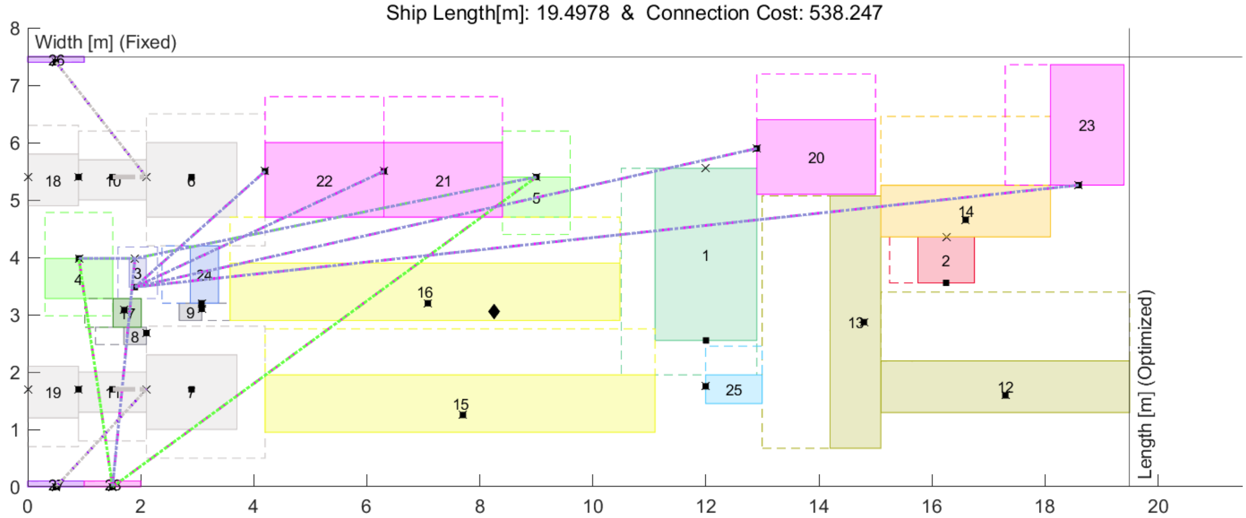
Solution No. 2

Ship Length[m]: 19.4978 & Connection Cost: 538.247



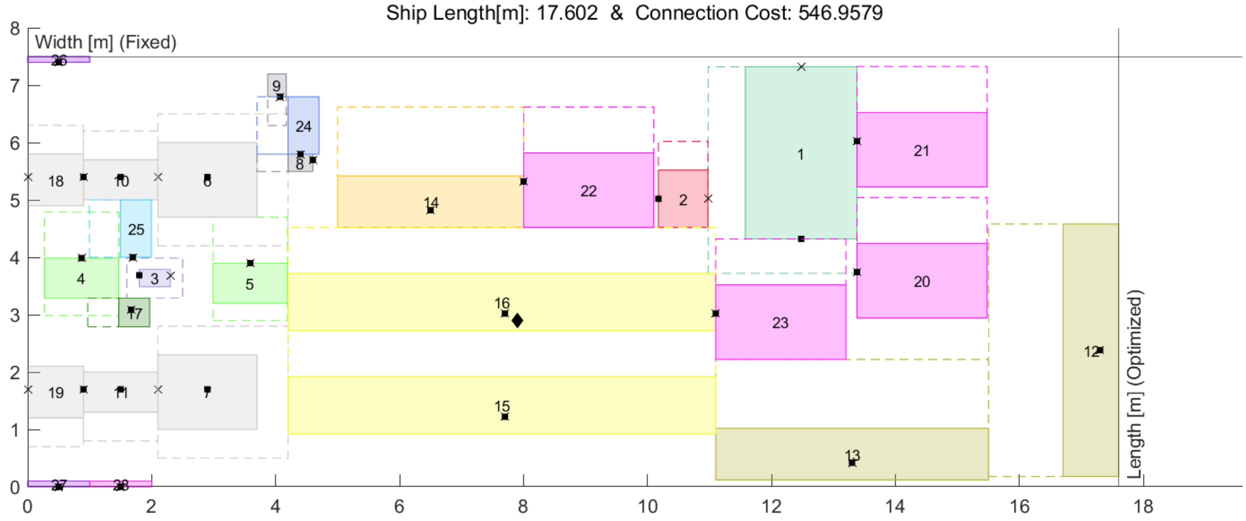
Solution No. 2

Ship Length[m]: 19.4978 & Connection Cost: 538.247



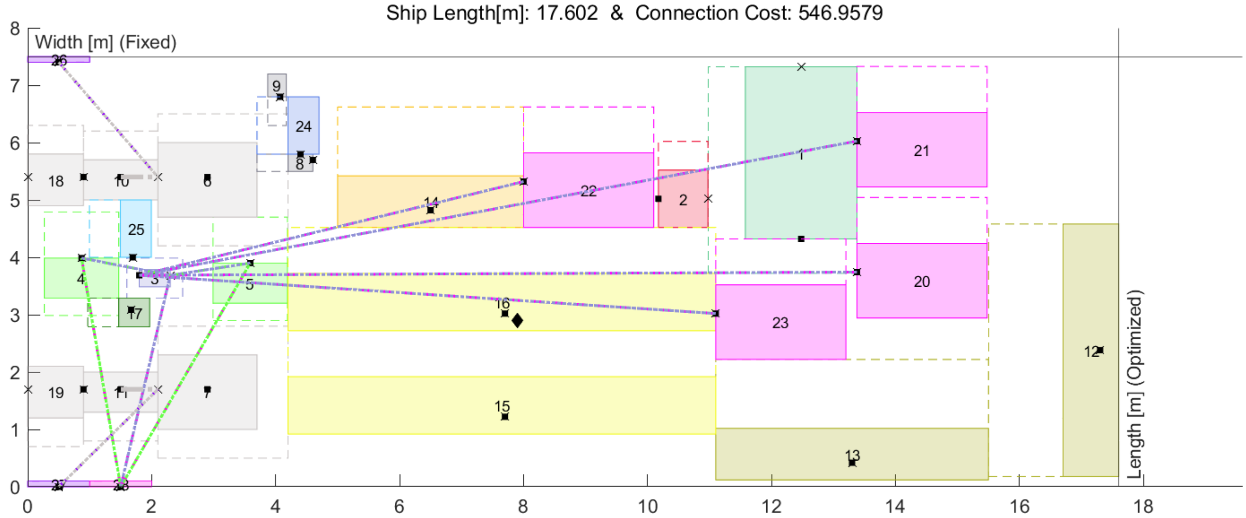
Solution No. 3

Ship Length[m]: 17.602 & Connection Cost: 546.9579



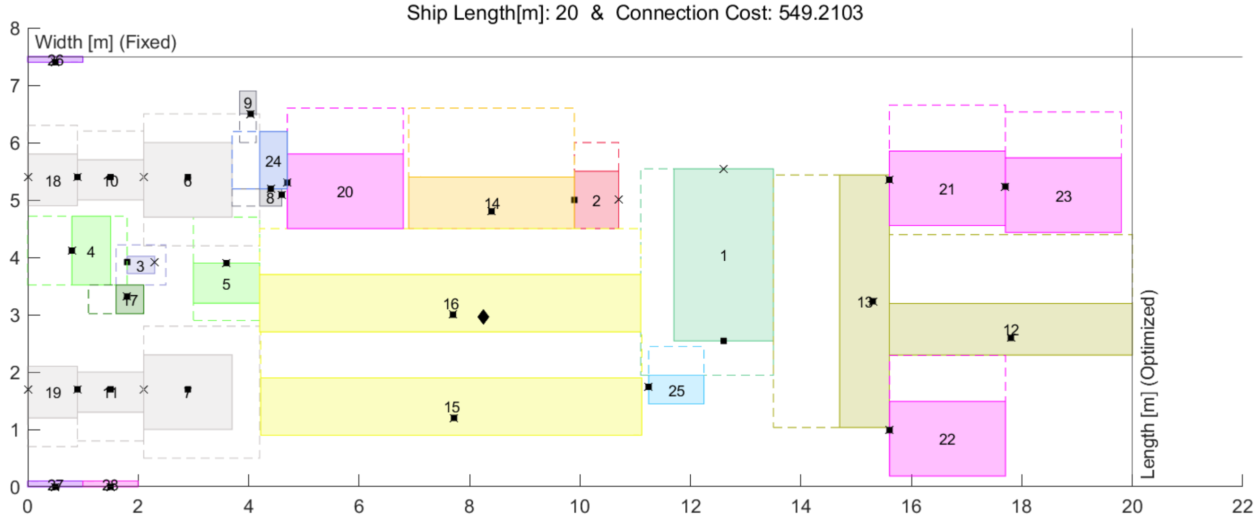
Solution No. 3

Ship Length[m]: 17.602 & Connection Cost: 546.9579



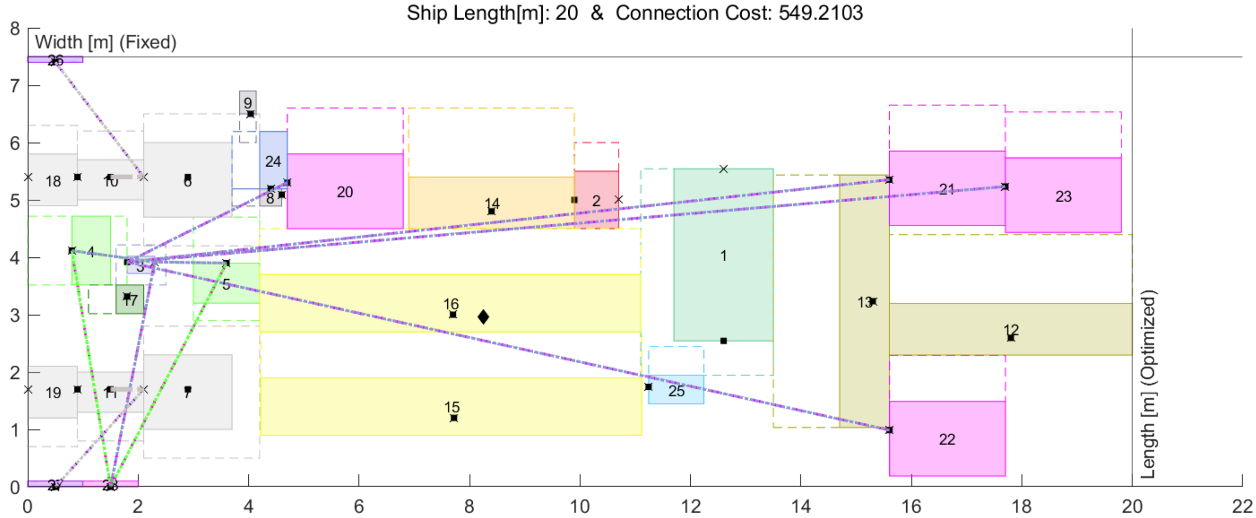
Solution No. 4

Ship Length[m]: 20 & Connection Cost: 549.2103



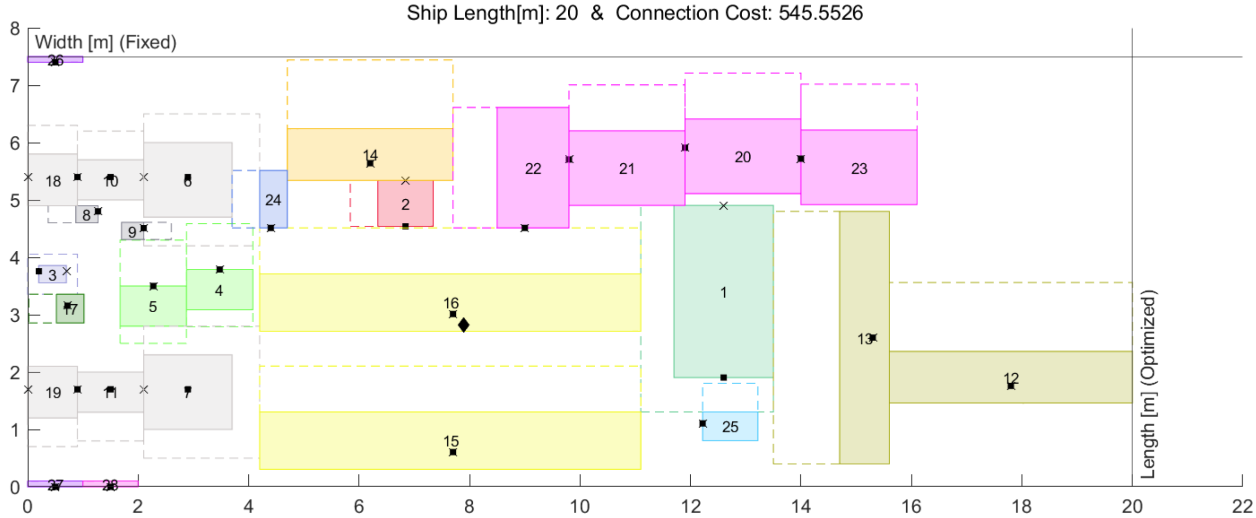
Solution No. 4

Ship Length[m]: 20 & Connection Cost: 549.2103



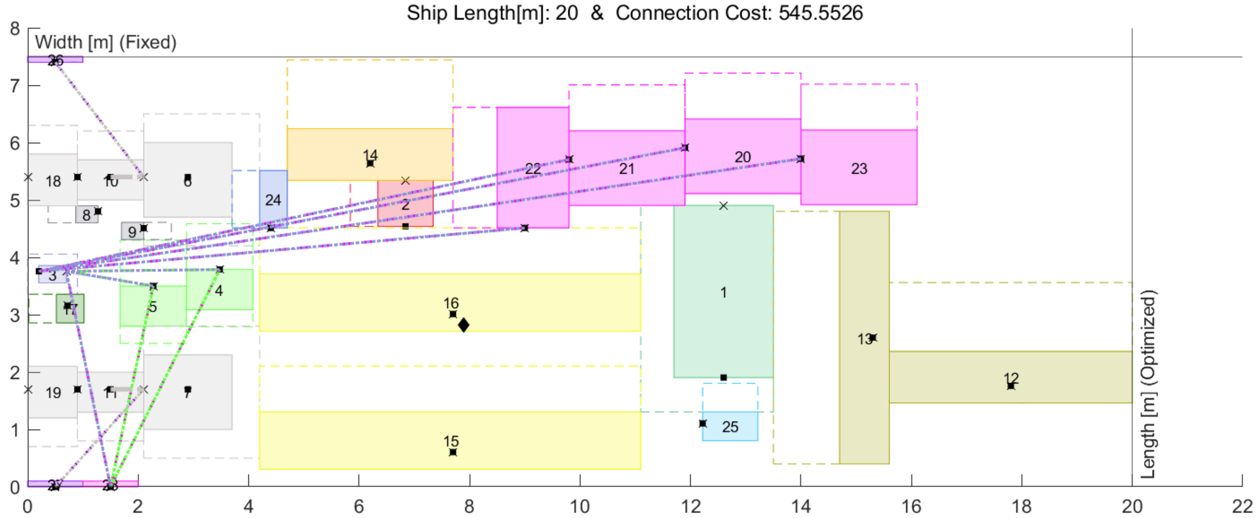
Solution No. 5

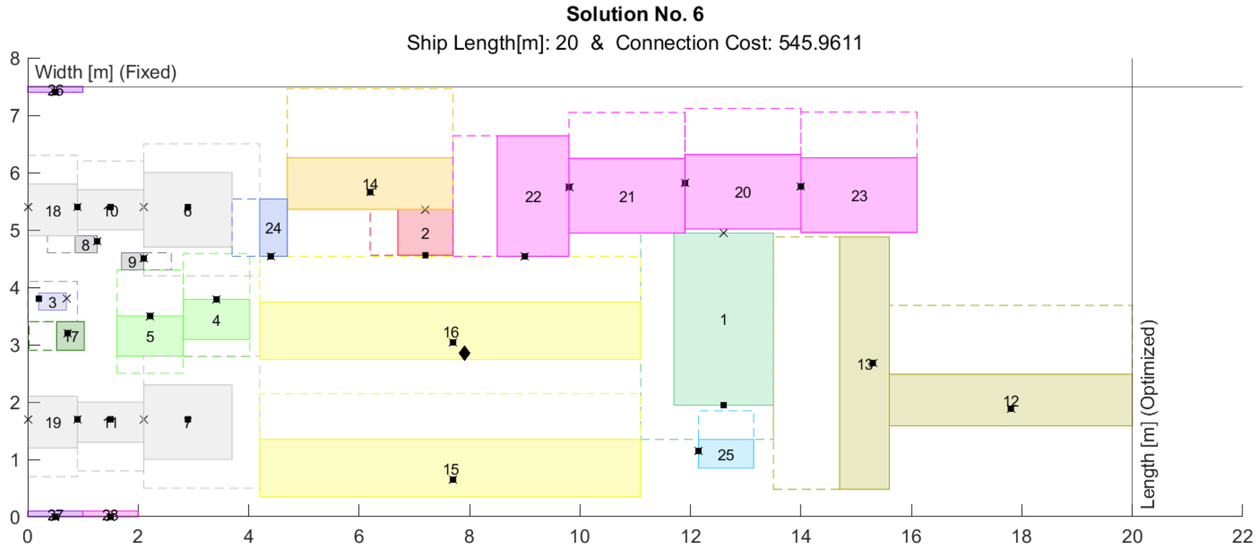
Ship Length[m]: 20 & Connection Cost: 545.5526

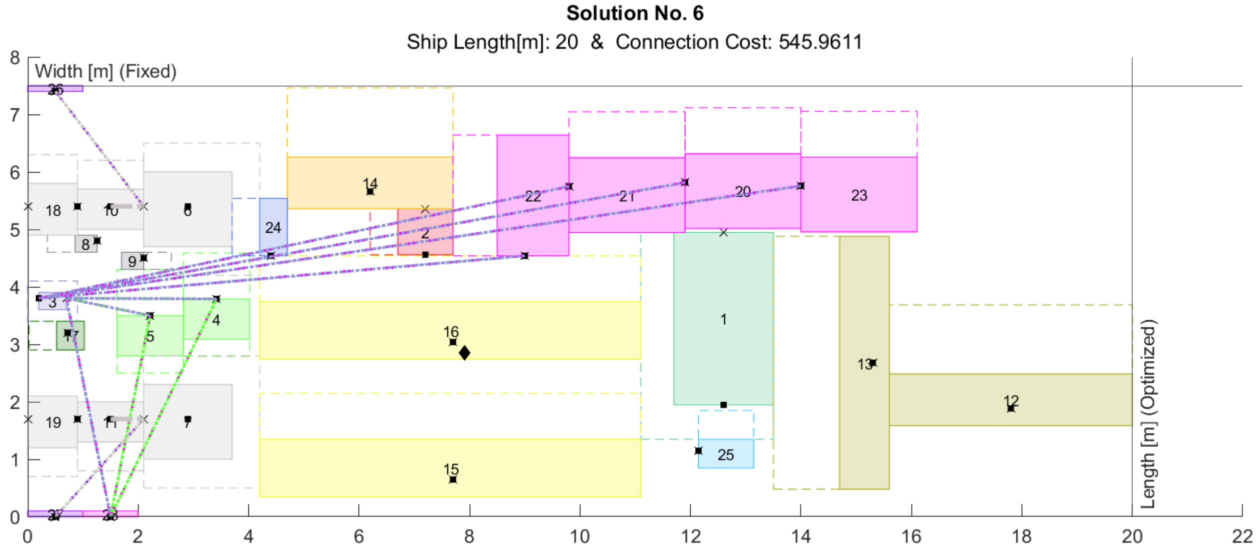


Solution No. 5

Ship Length[m]: 20 & Connection Cost: 545.5526




Solution No. 6
Ship Length[m]: 20 & Connection Cost: 545.9611
Width [m] (Fixed)
Length [m] (Optimized)

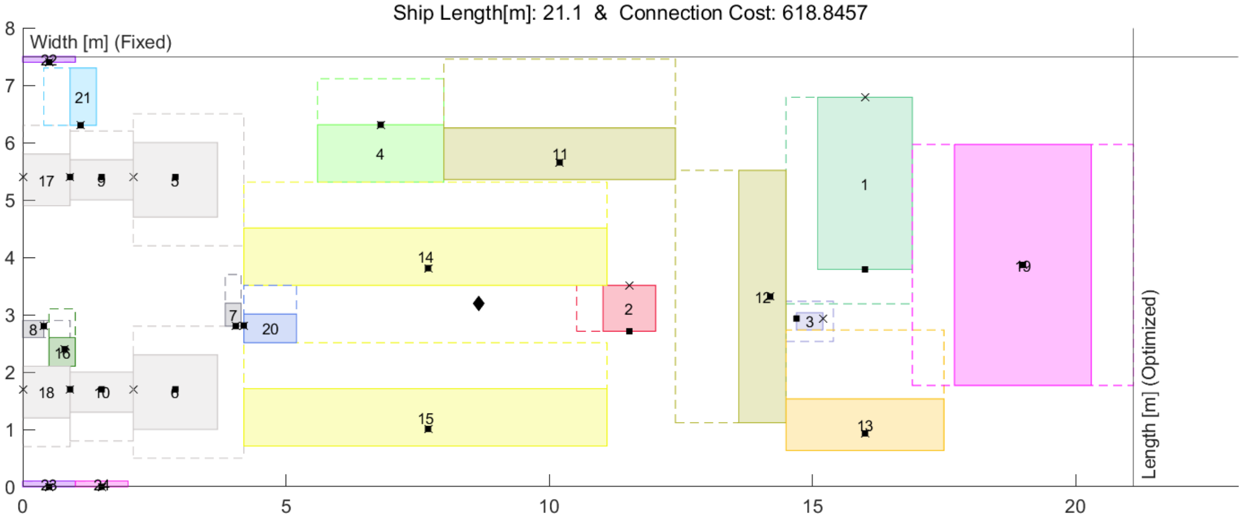

Solution No. 6
Ship Length[m]: 20 & Connection Cost: 545.9611
Width [m] (Fixed)
Length [m] (Optimized)

B.1.2. Test 2: Methanol Reformers and Fuel Cells grouped

	BlockName
1	"Methanol Fuel Preparation"
2	"Diesel Day Supply"
3	"Hydrogen Supply"
4	"Fuel Cells"
5	"Main Engine (1)"
6	"Main Engine (2)"
7	"ESM Converter (1)"
8	"ESM Converter (2)"
9	"ESM Machine (1)"
10	"ESM Machine (2)"
11	"DC Distribution (1)"
12	"DC Distribution (2)"
13	"AC Distribution (1)"
14	"Battery (1)"
15	"Battery (2)"
16	"Nitrogen Tank"
17	"Mechanical Transmission (1)"
18	"Mechanical Transmission (2)"
19	"Methanol Reformers"
20	"Central Cooling Water"
21	"Fresh Water Tank"
22	"Exhaust Interface PS (1)"
23	"Exhaust Interface SS (2)"
24	"H2 Exhaust Interface"

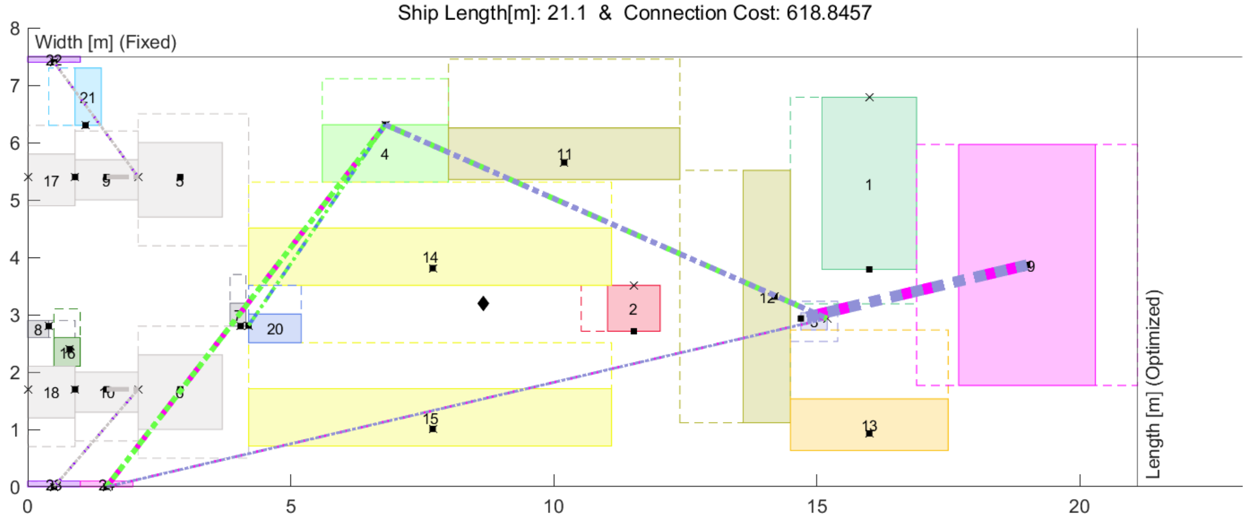
Solution No. 1

Ship Length[m]: 21.1 & Connection Cost: 618.8457



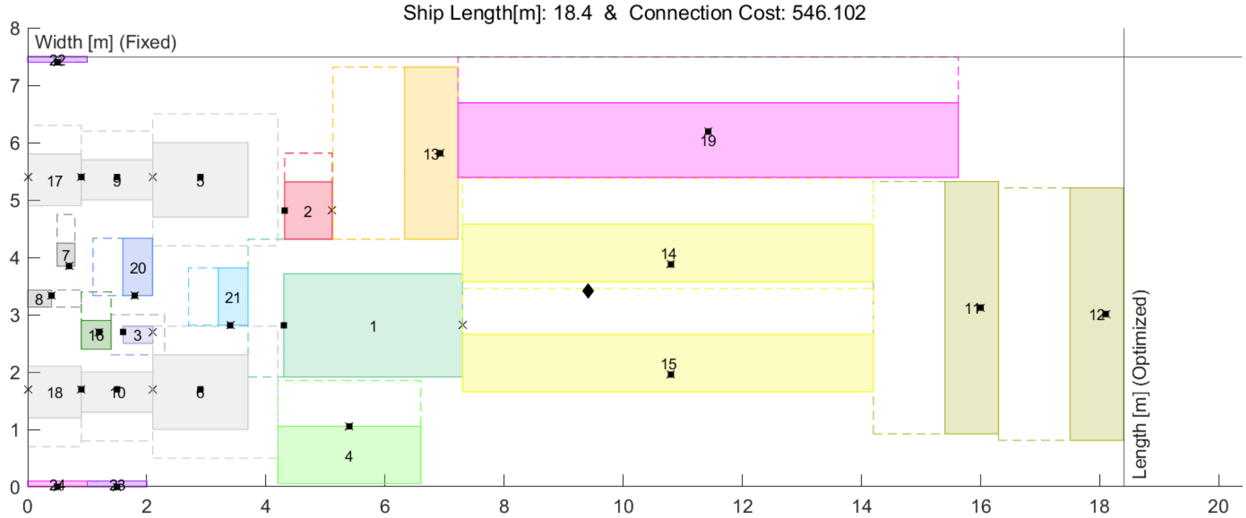
Solution No. 1

Ship Length[m]: 21.1 & Connection Cost: 618.8457



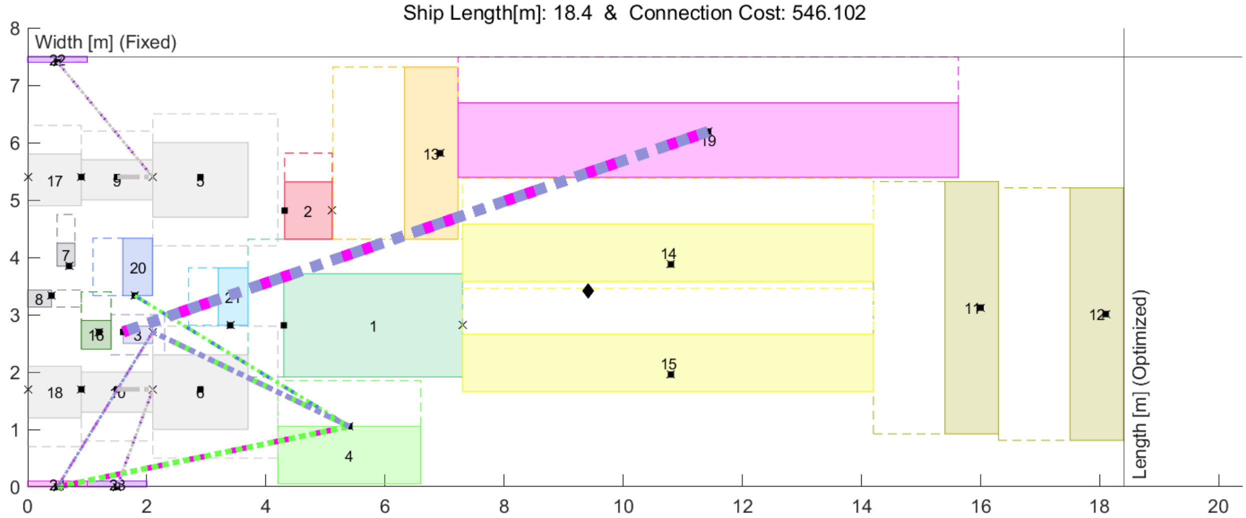
Solution No. 2

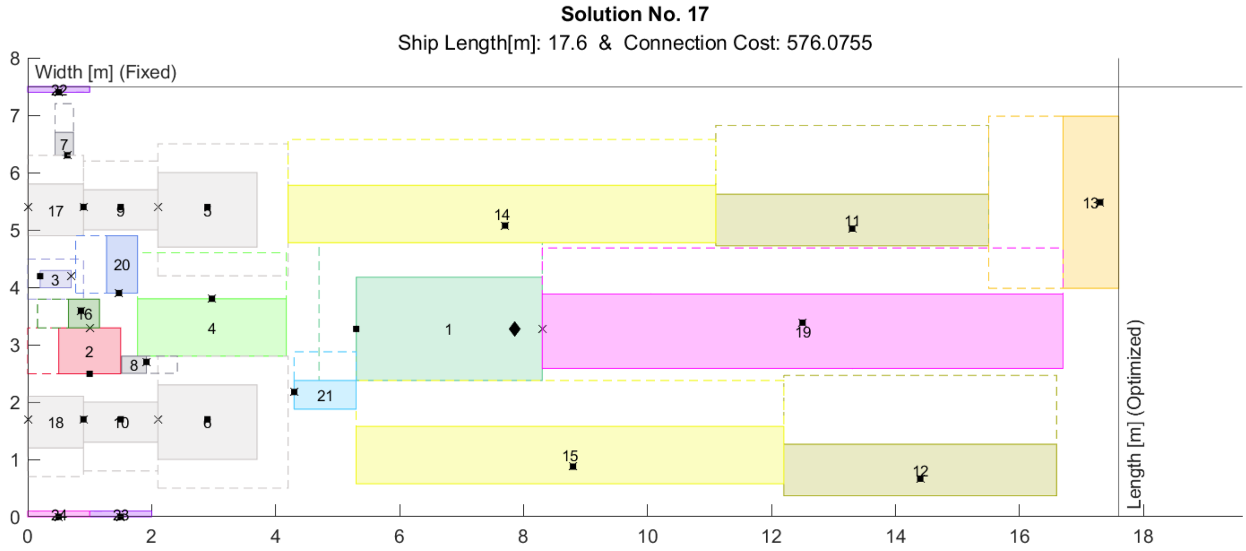
Ship Length[m]: 18.4 & Connection Cost: 546.102

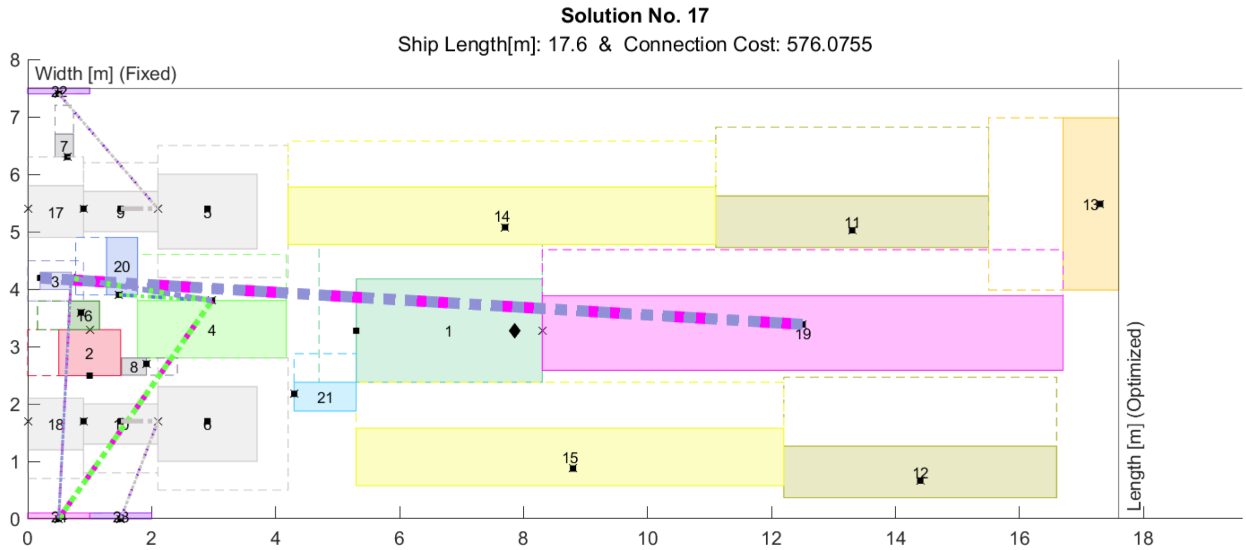


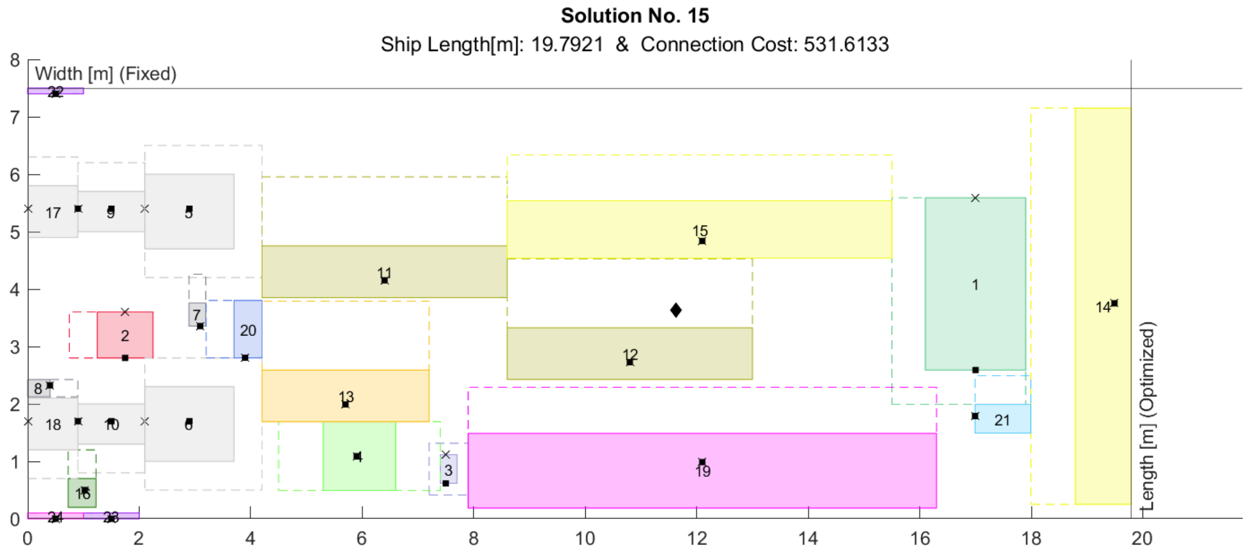
Solution No. 2

Ship Length[m]: 18.4 & Connection Cost: 546.102



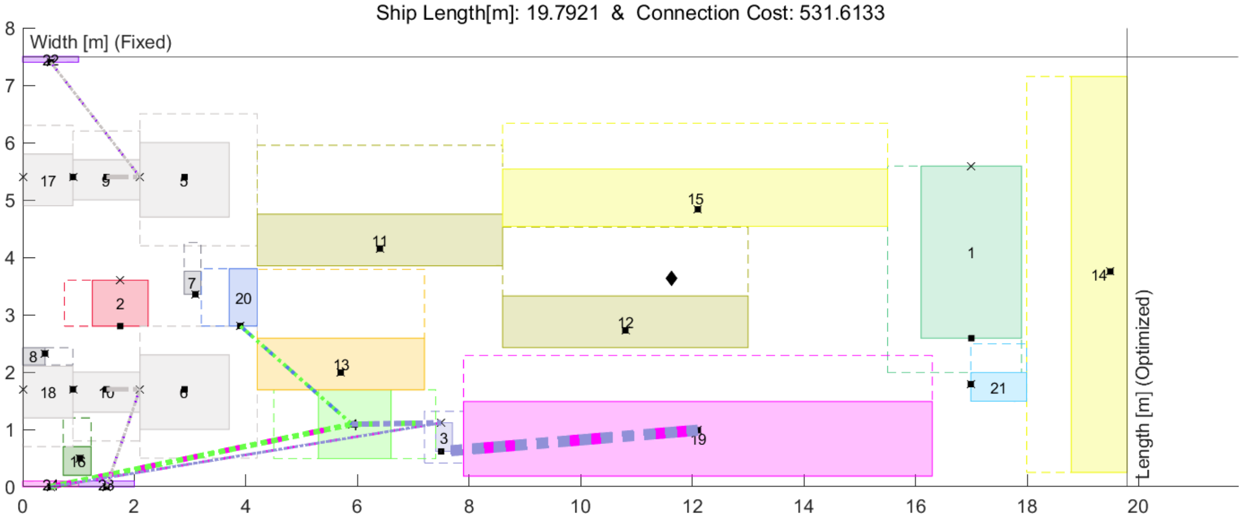

Solution No. 17
Ship Length[m]: 17.6 & Connection Cost: 576.0755
Width [m] (Fixed)
Length [m] (Optimized)
0 2 4 6 8 10 12 14 16 18
0 1 2 3 4 5 6 7 8
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 17 18 19 20 21


Solution No. 17
Ship Length[m]: 17.6 & Connection Cost: 576.0755
Width [m] (Fixed)
Length [m] (Optimized)
0 2 4 6 8 10 12 14 16 18
0 1 2 3 4 5 6 7 8
1 2 3 4 5 6 7 8 11 12 13 14 15 17 18 19 20 21


Solution No. 15
Ship Length[m]: 19.7921 & Connection Cost: 531.6133
Width [m] (Fixed)
Length [m] (Optimized)
0 2 4 6 8 10 12 14 16 18 20
0 1 2 3 4 5 6 7 8
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21

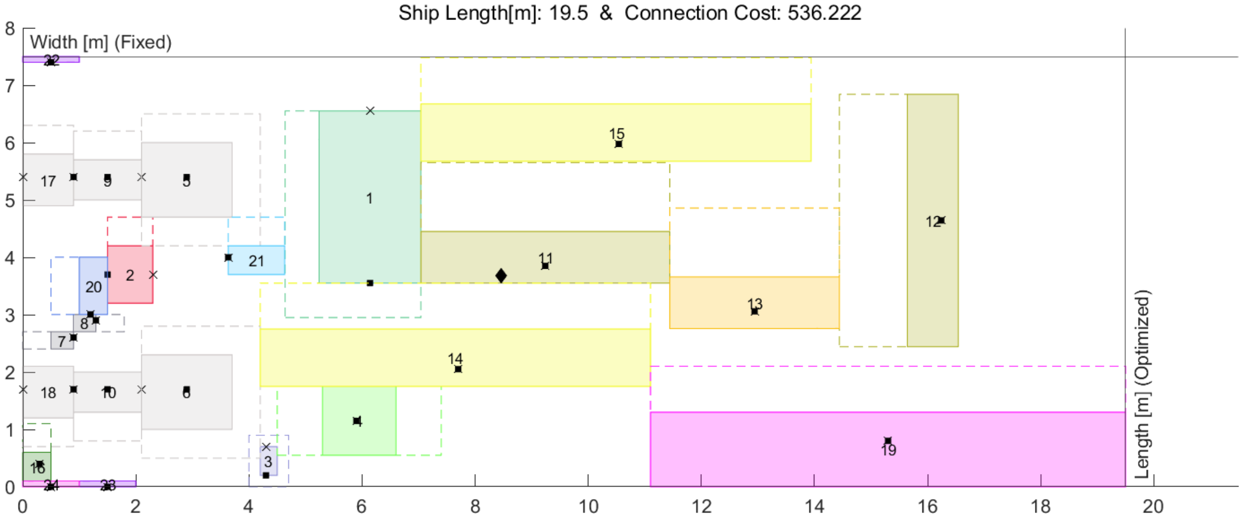
Solution No. 15

Ship Length[m]: 19.7921 & Connection Cost: 531.6133



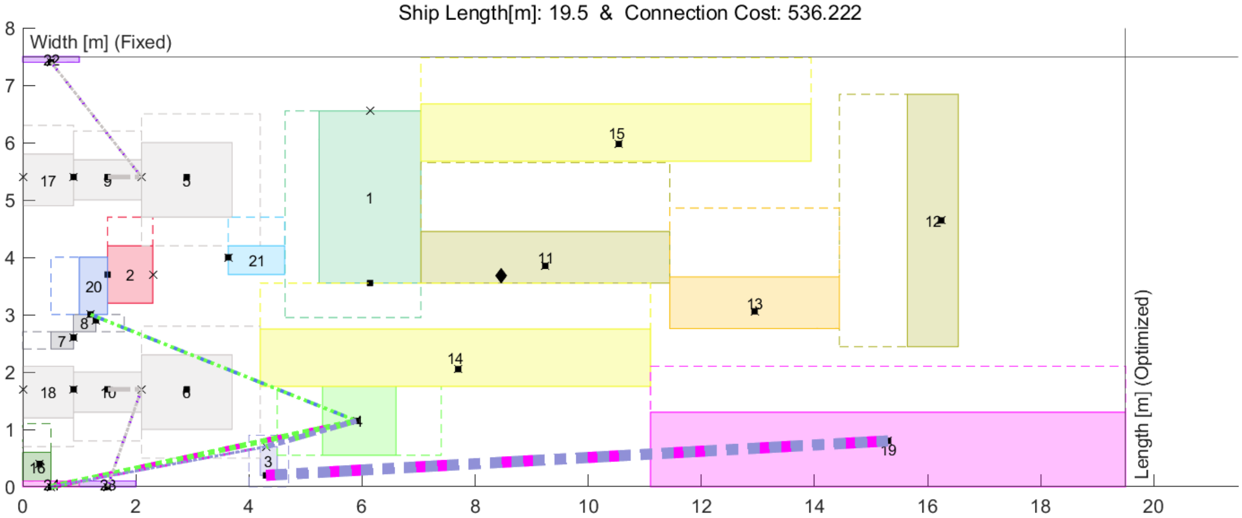
Solution No. 6

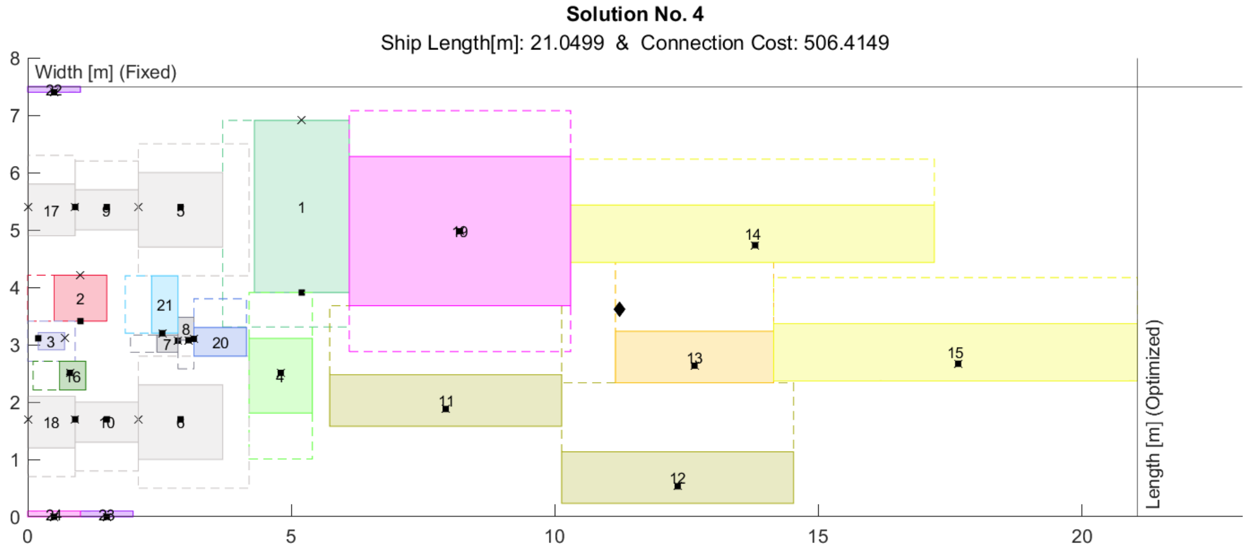
Ship Length[m]: 19.5 & Connection Cost: 536.222

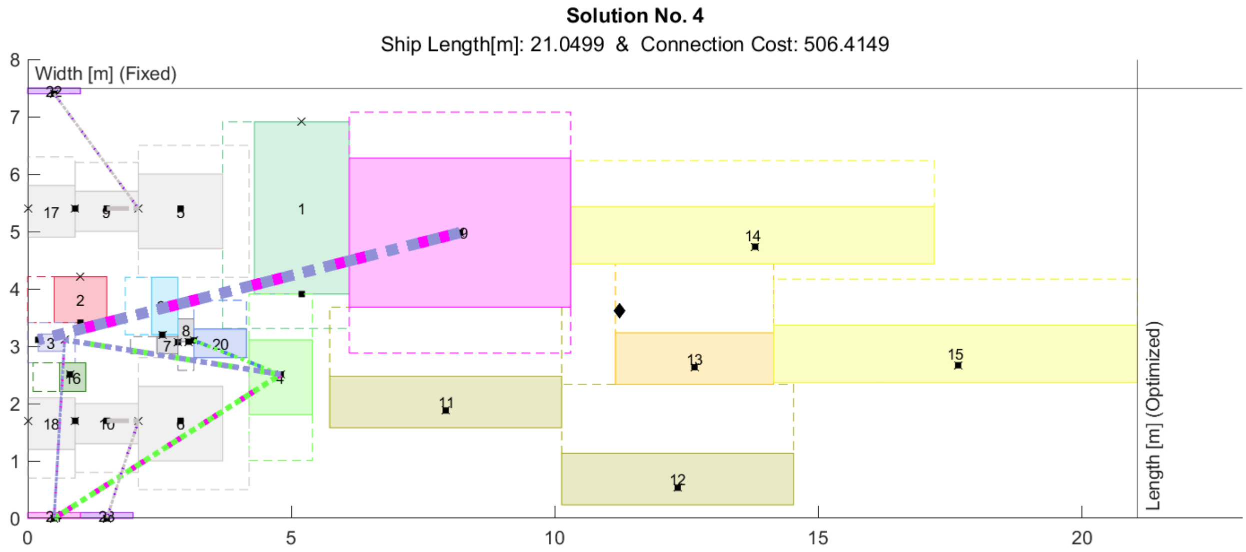


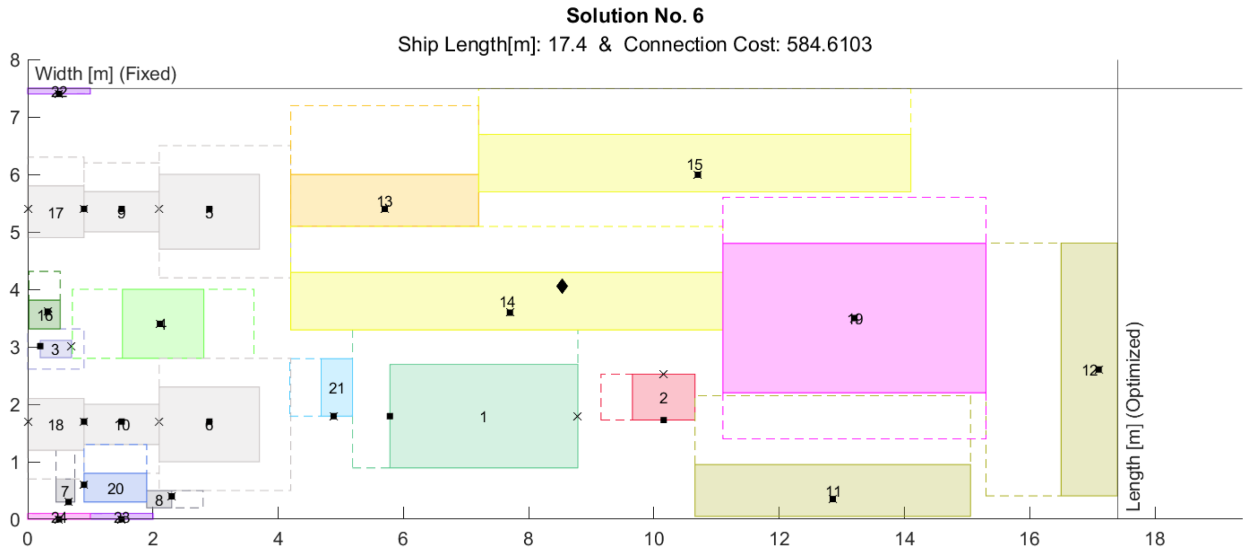
Solution No. 6

Ship Length[m]: 19.5 & Connection Cost: 536.222



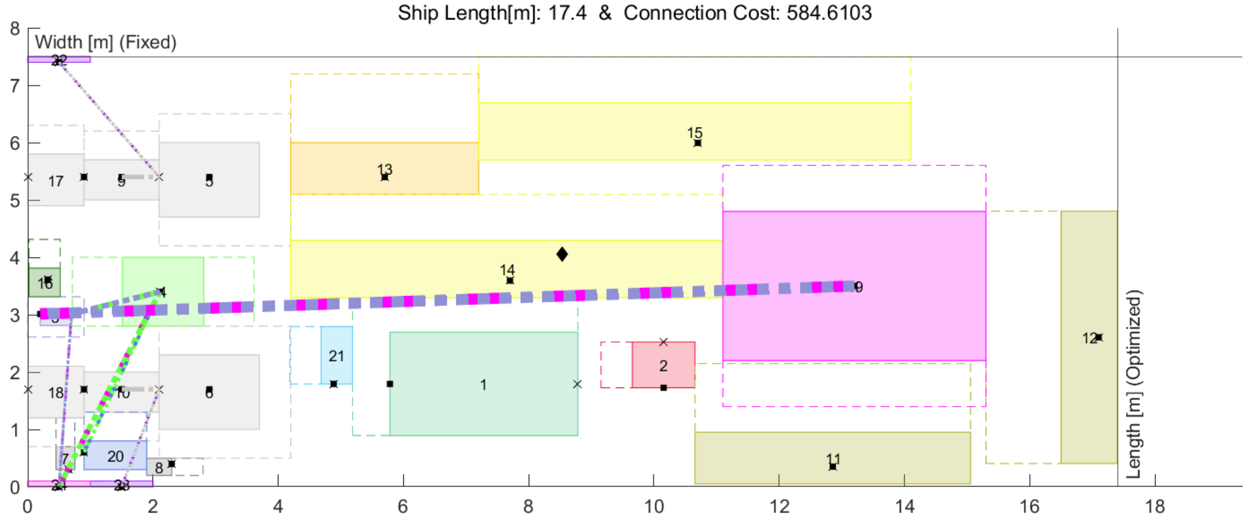

Solution No. 4
Ship Length[m]: 21.0499 & Connection Cost: 506.4149
Width [m] (Fixed)
Length [m] (Optimized)


Solution No. 4
Ship Length[m]: 21.0499 & Connection Cost: 506.4149
Width [m] (Fixed)
Length [m] (Optimized)


Solution No. 6
Ship Length[m]: 17.4 & Connection Cost: 584.6103
Width [m] (Fixed)
Length [m] (Optimized)

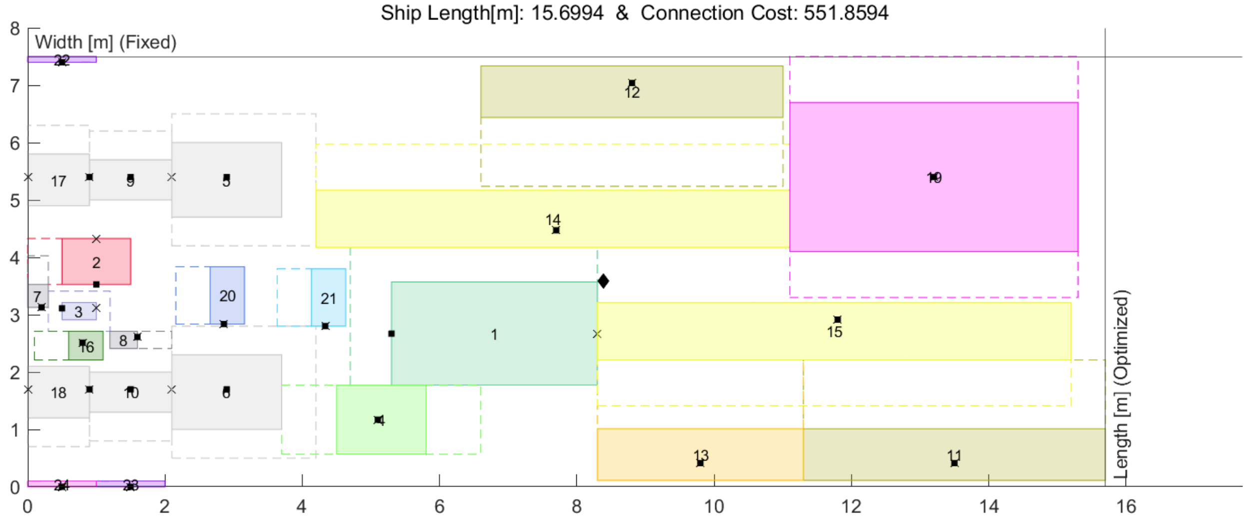
Solution No. 6

Ship Length[m]: 17.4 & Connection Cost: 584.6103



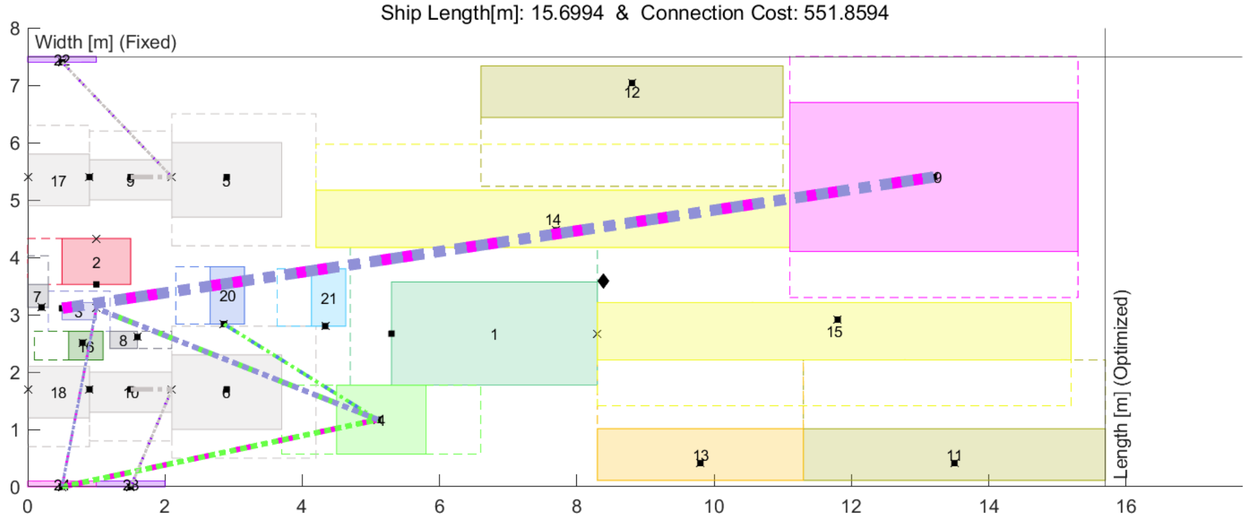
Solution No. 9

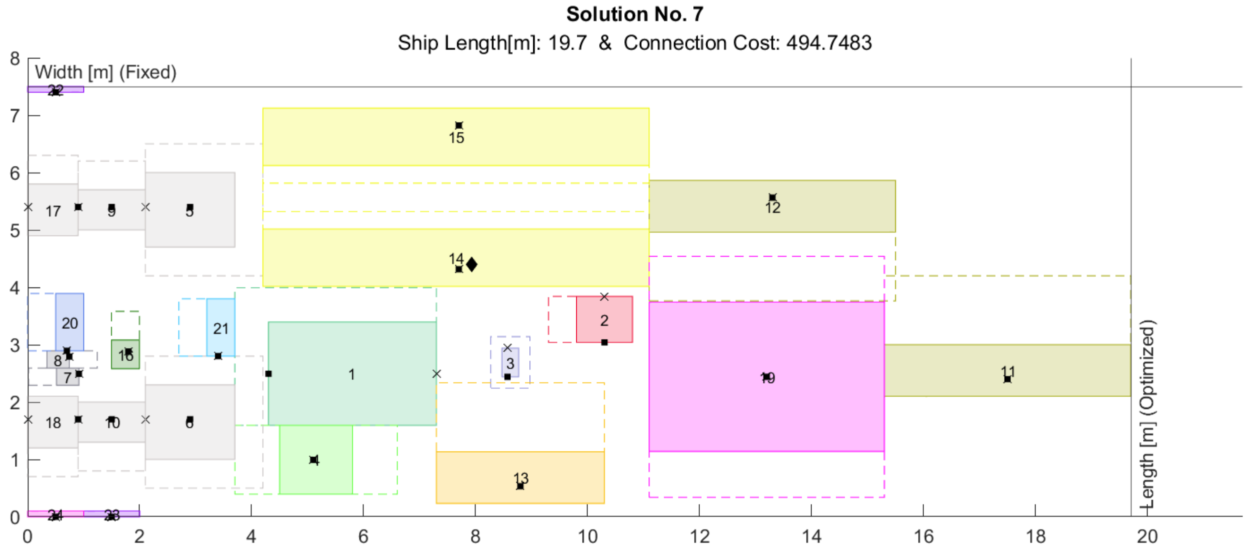
Ship Length[m]: 15.6994 & Connection Cost: 551.8594

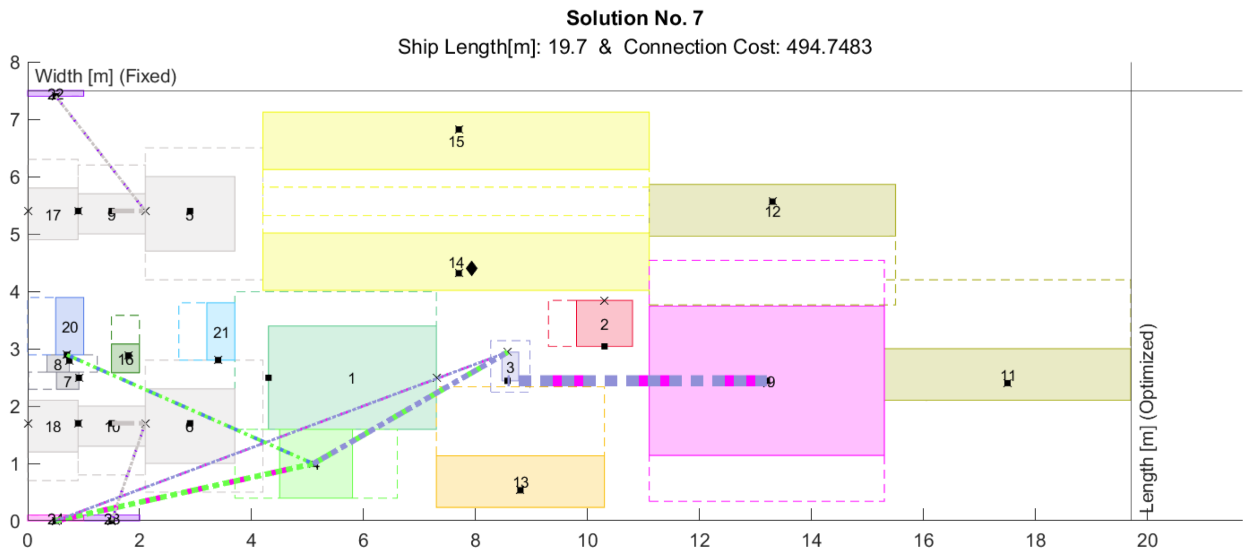


Solution No. 9

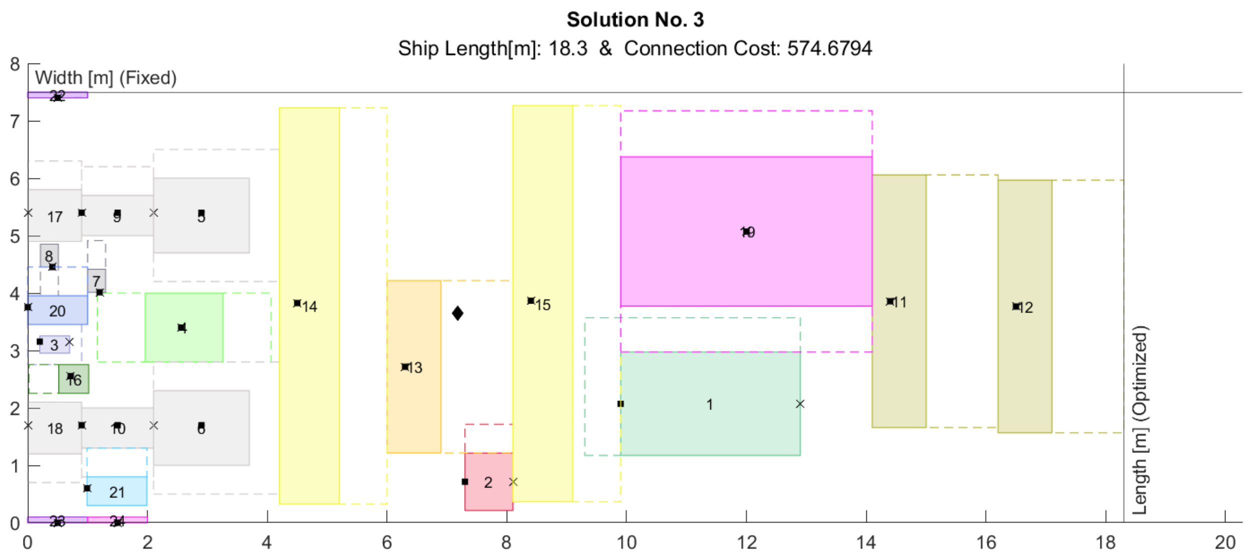
Ship Length[m]: 15.6994 & Connection Cost: 551.8594



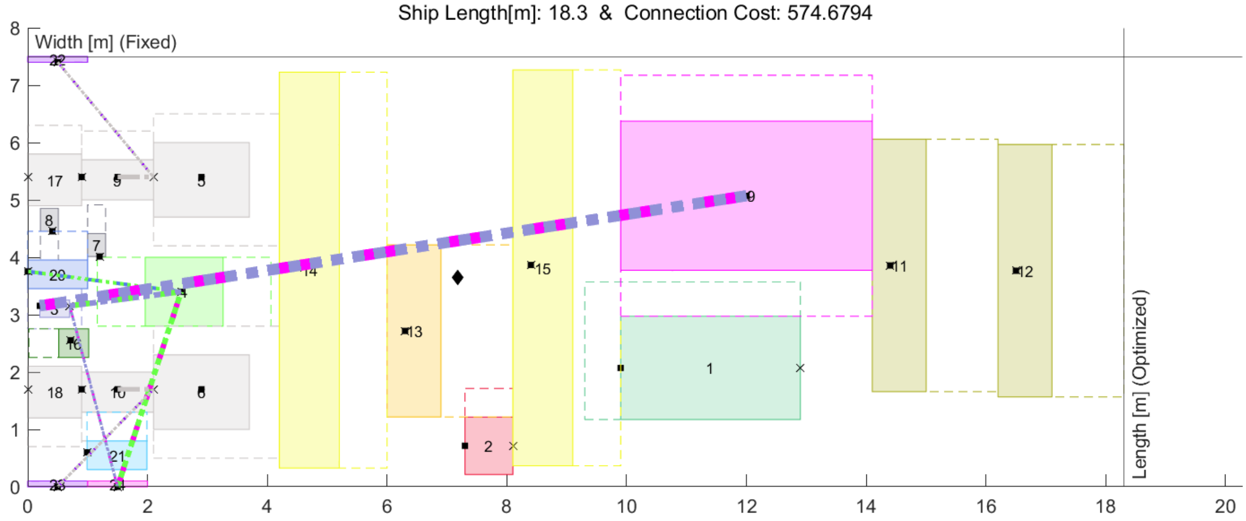




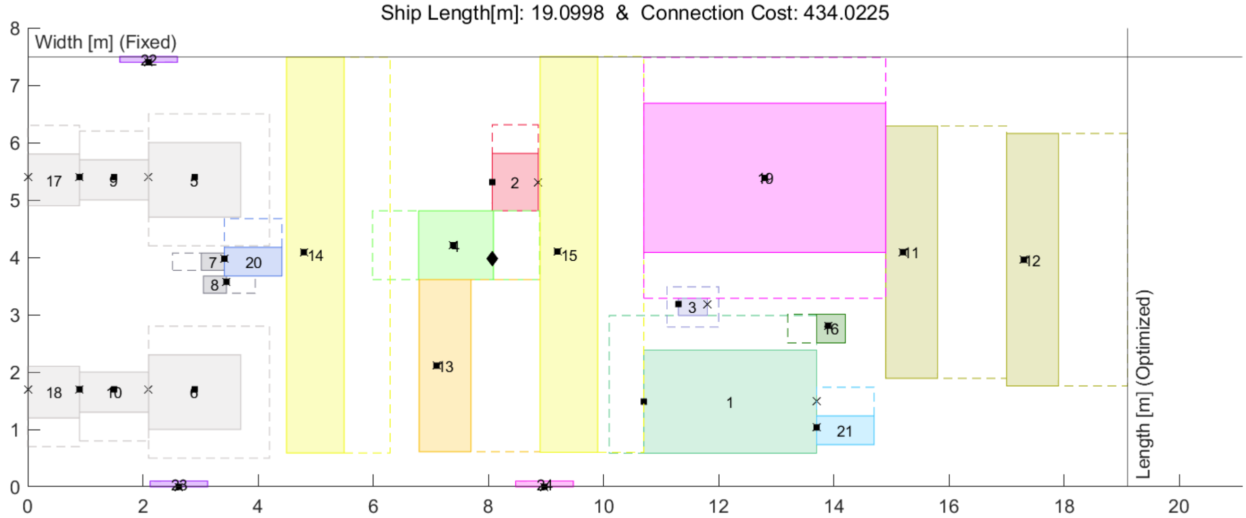
B.1.3. Test 3:Transverse Rotational Constraint on BGs



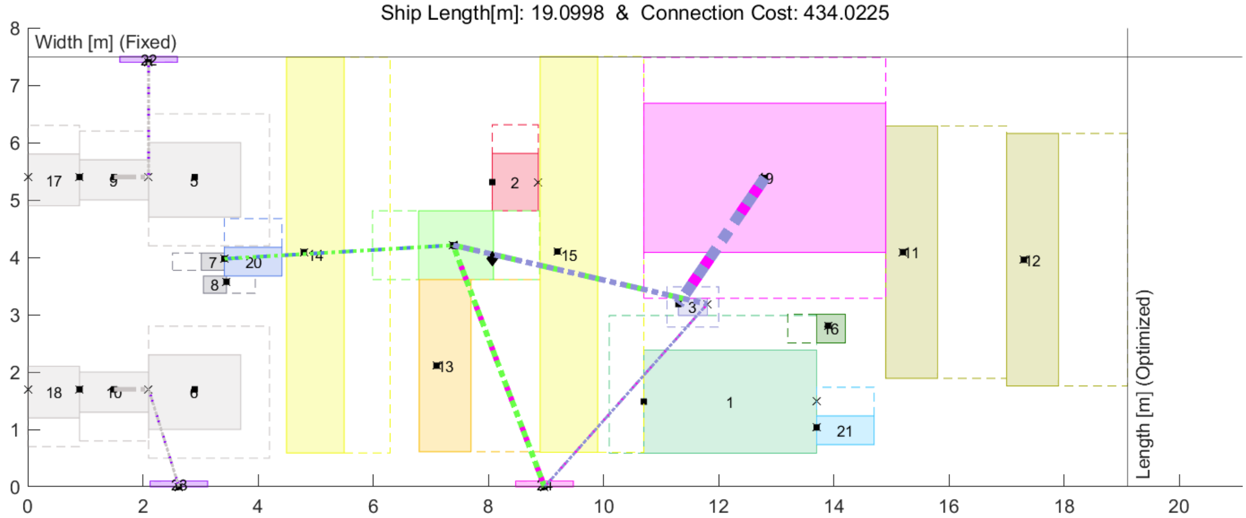
Solution No. 3
Ship Length[m]: 18.3 & Connection Cost: 574.6794

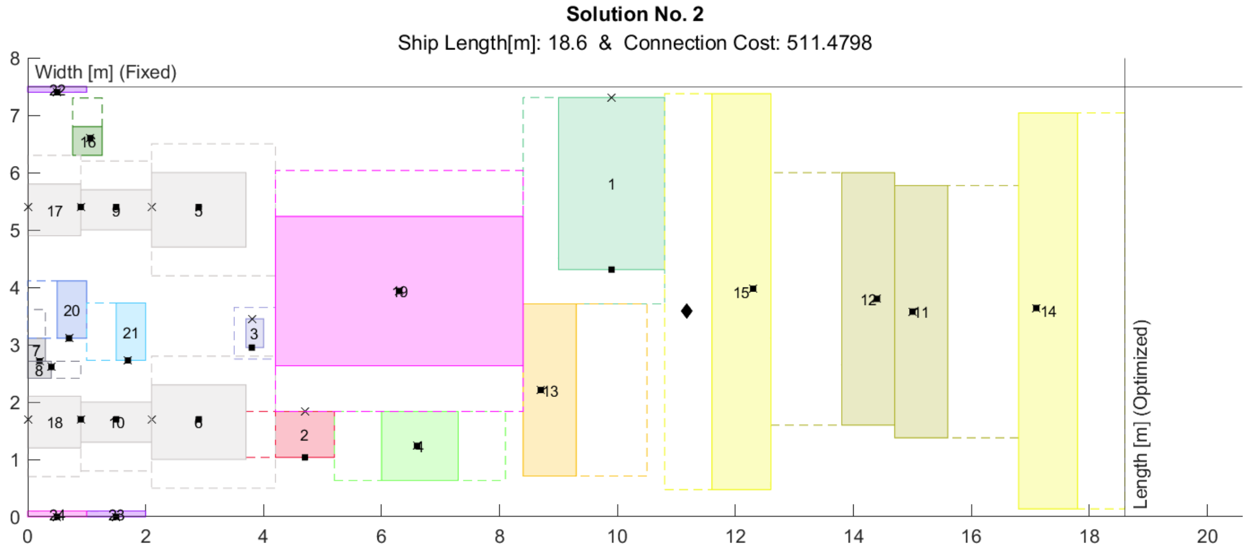


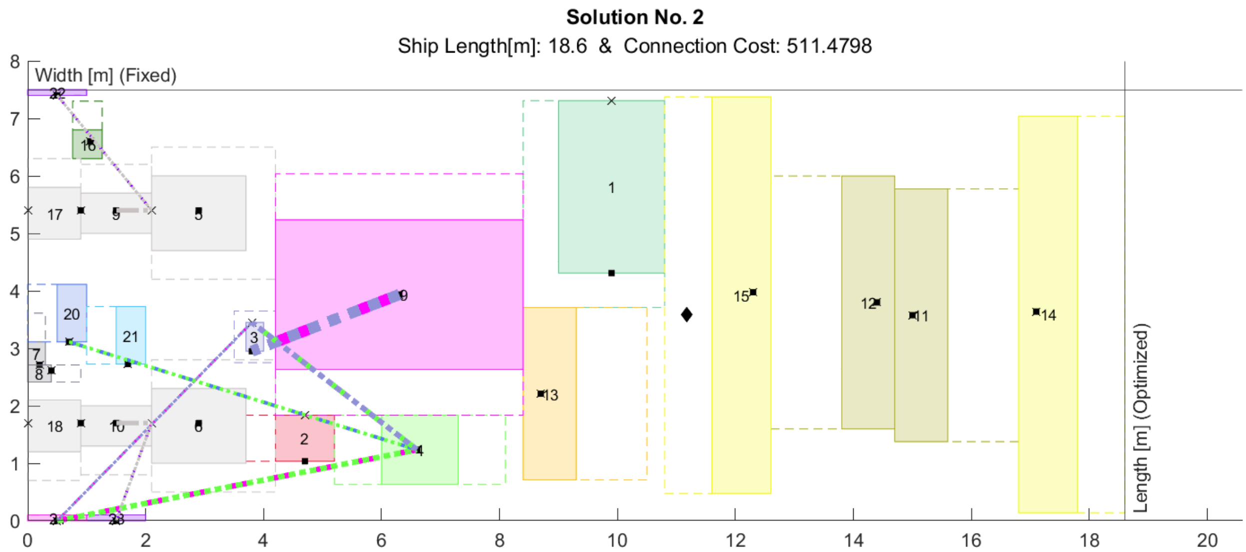
Solution No. 5
Ship Length[m]: 19.0998 & Connection Cost: 434.0225

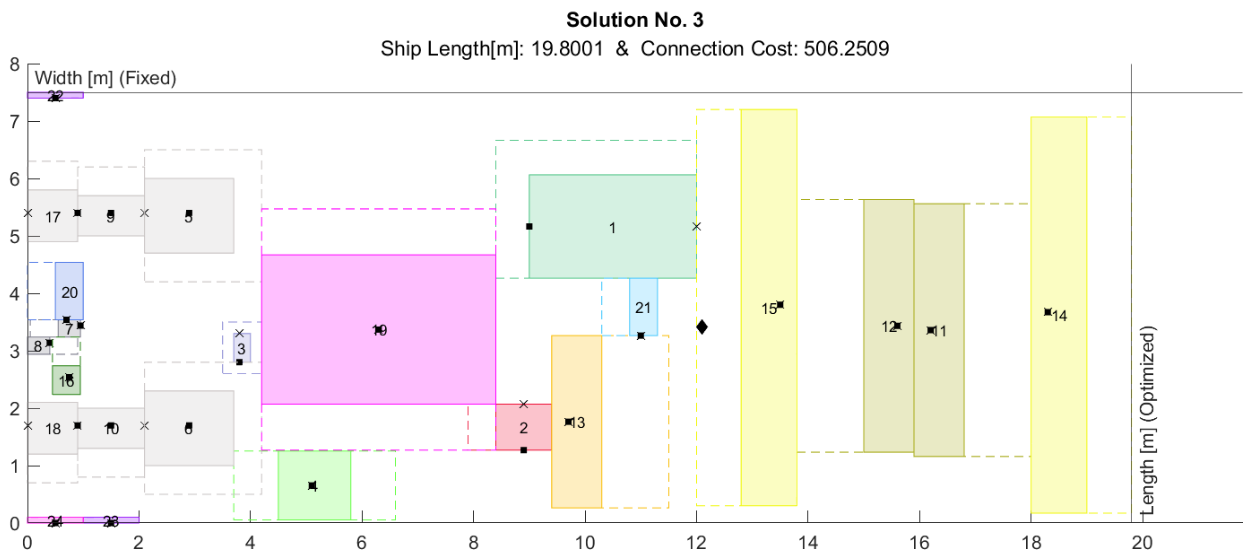


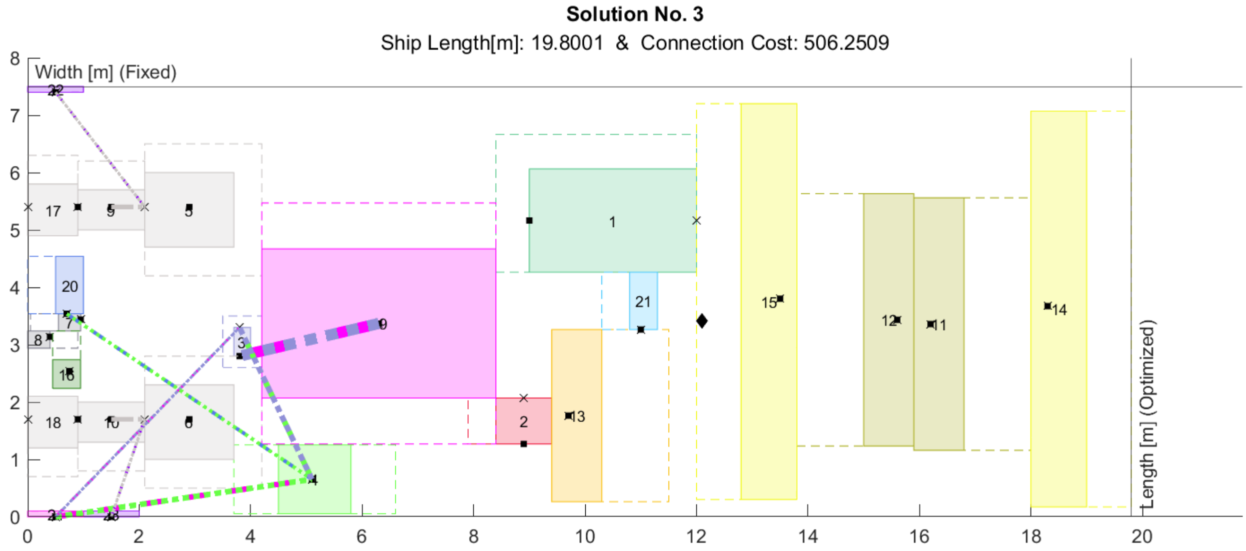
Solution No. 5
Ship Length[m]: 19.0998 & Connection Cost: 434.0225



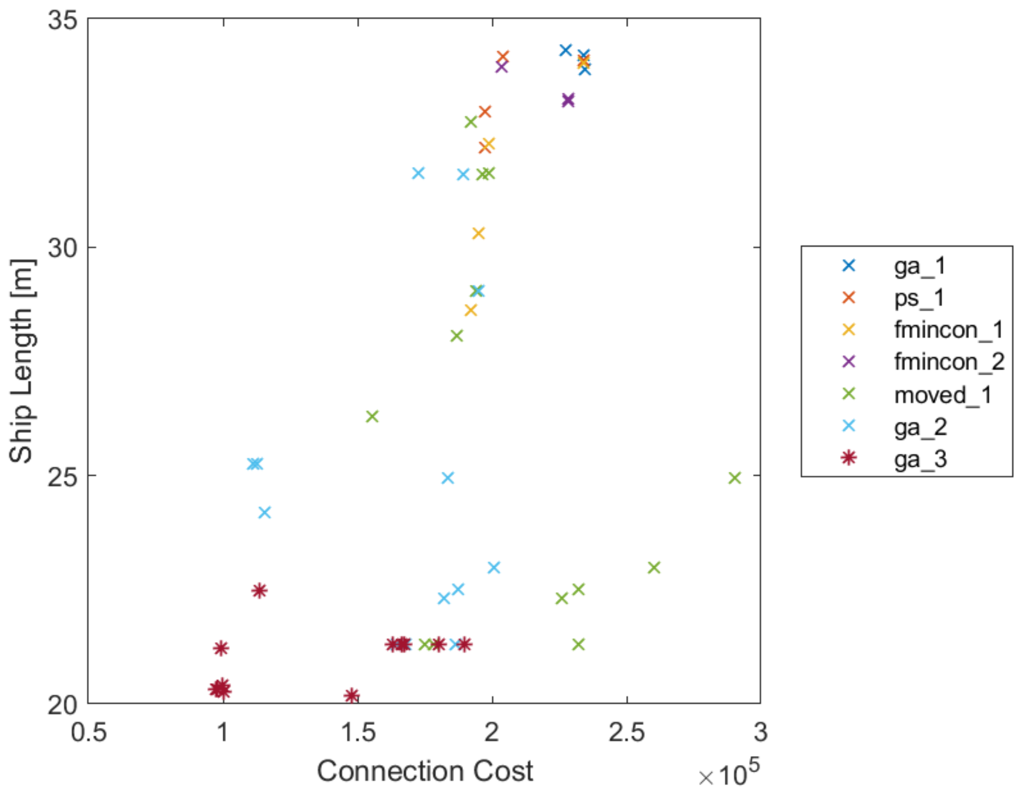

Solution No. 2
Ship Length[m]: 18.6 & Connection Cost: 511.4798
Width [m] (Fixed)
Length [m] (Optimized)


Solution No. 2
Ship Length[m]: 18.6 & Connection Cost: 511.4798
Width [m] (Fixed)
Length [m] (Optimized)


Solution No. 3
Ship Length[m]: 19.8001 & Connection Cost: 506.2509
Width [m] (Fixed)
Length [m] (Optimized)

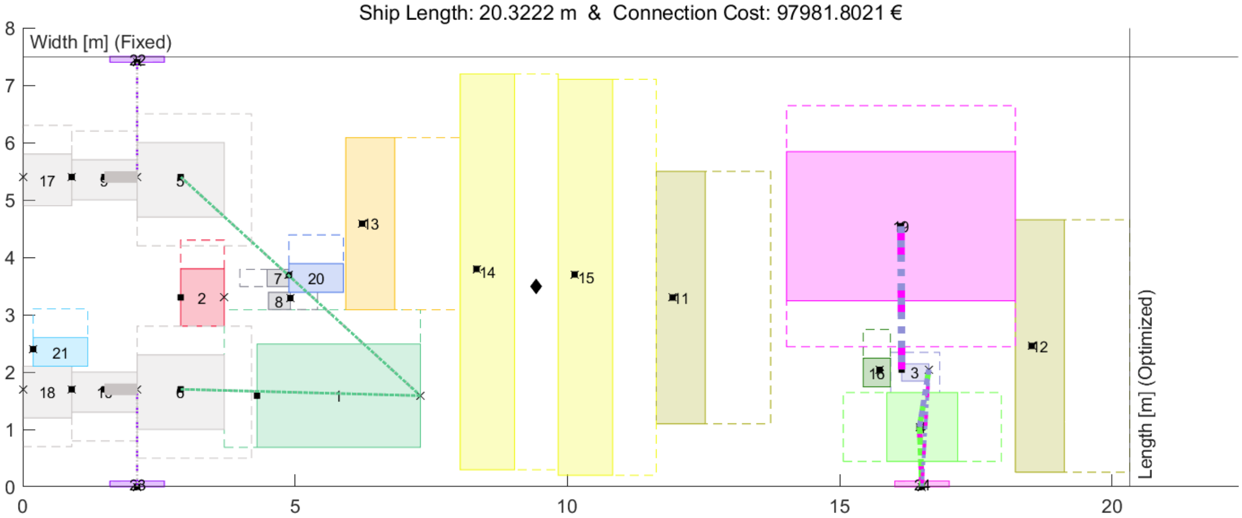


B.2. Actual Connection Matrix Tests



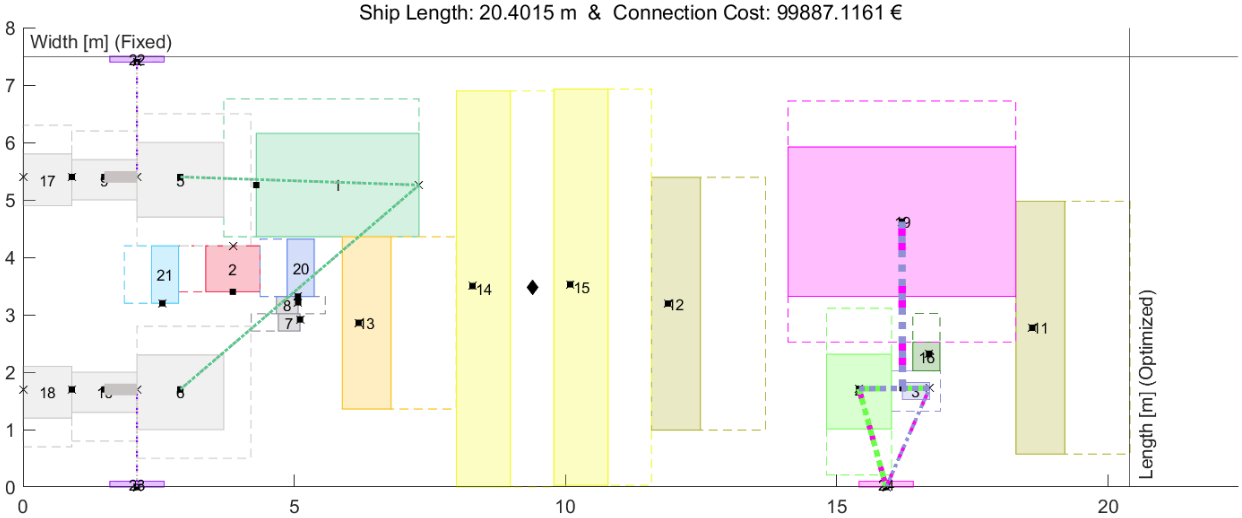
Solution No. 1

Ship Length: 20.3222 m & Connection Cost: 97981.8021 €



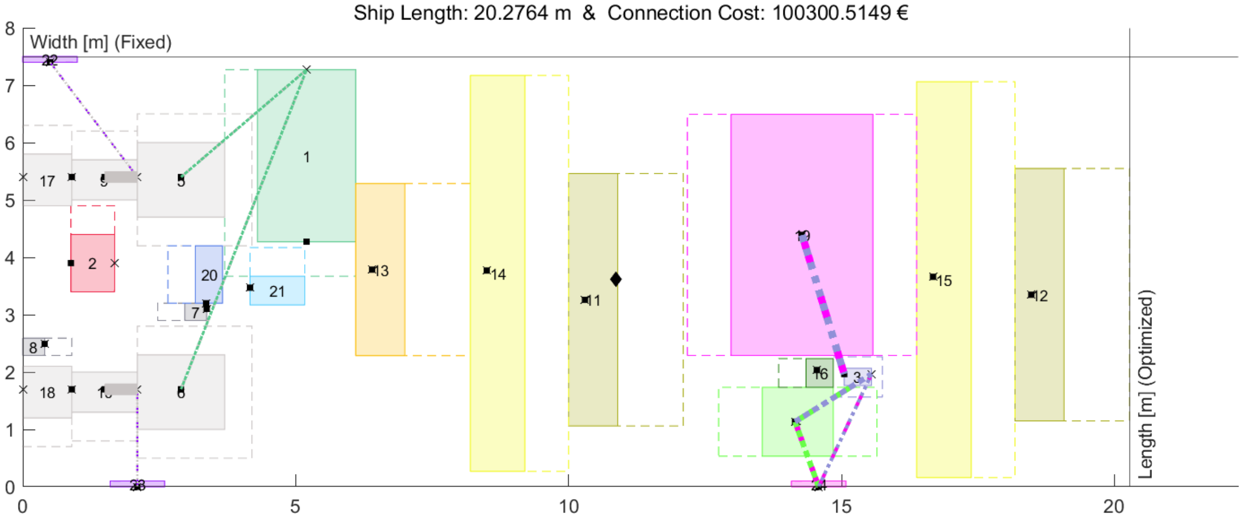
Solution No. 2

Ship Length: 20.4015 m & Connection Cost: 99887.1161 €



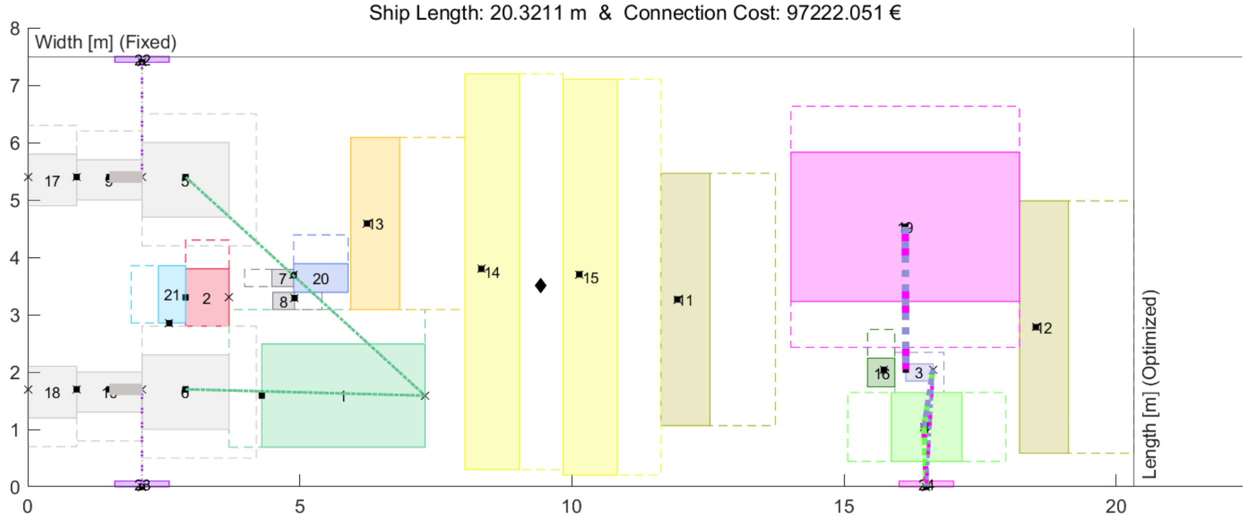
Solution No. 3

Ship Length: 20.2764 m & Connection Cost: 100300.5149 €



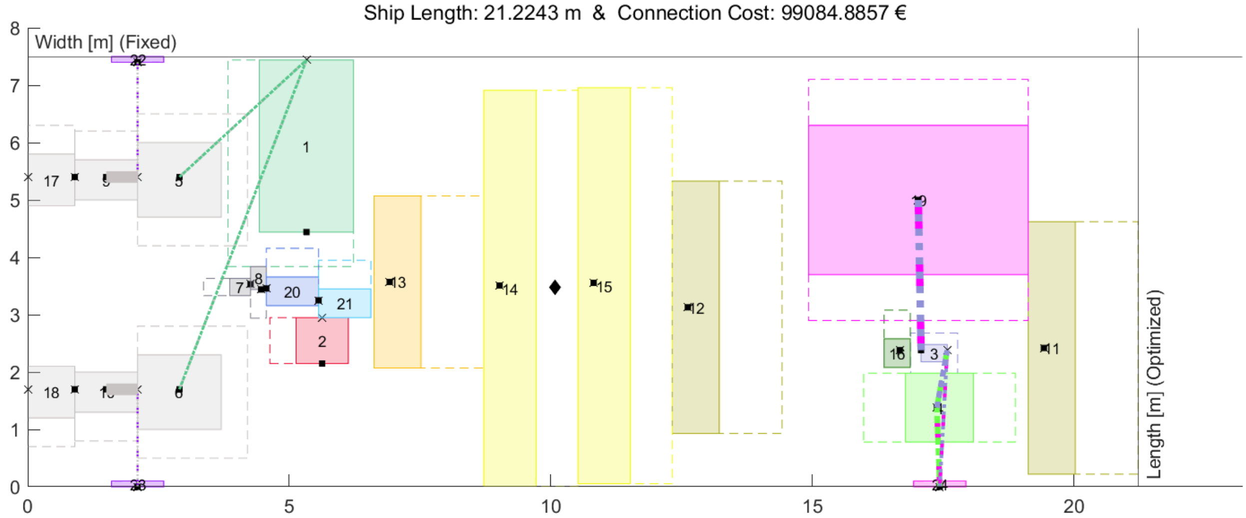
Solution No. 4

Ship Length: 20.3211 m & Connection Cost: 97222.051 €



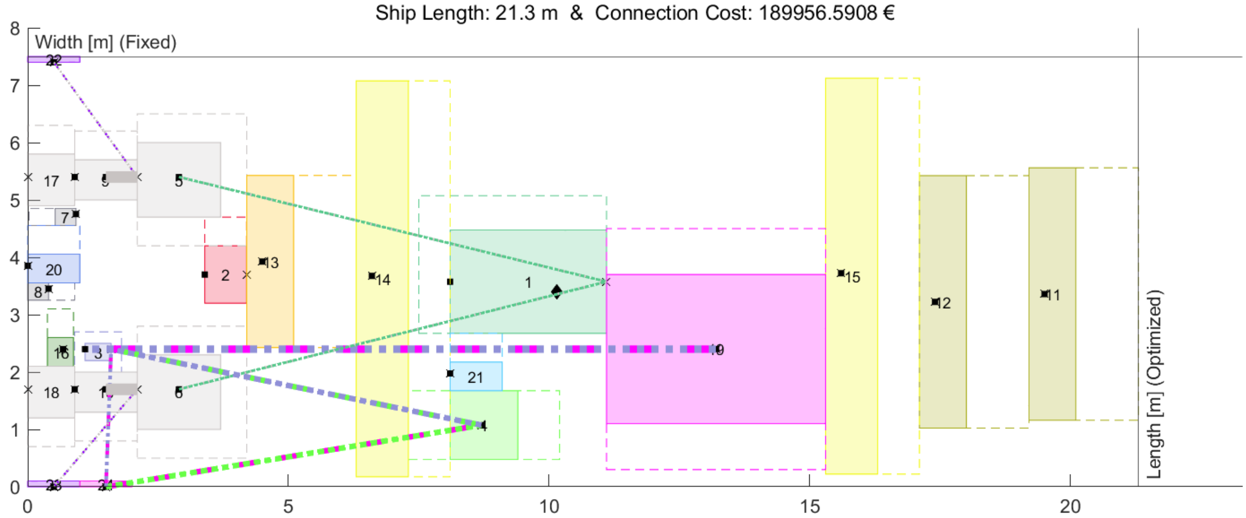
Solution No. 5

Ship Length: 21.2243 m & Connection Cost: 99084.8857 €



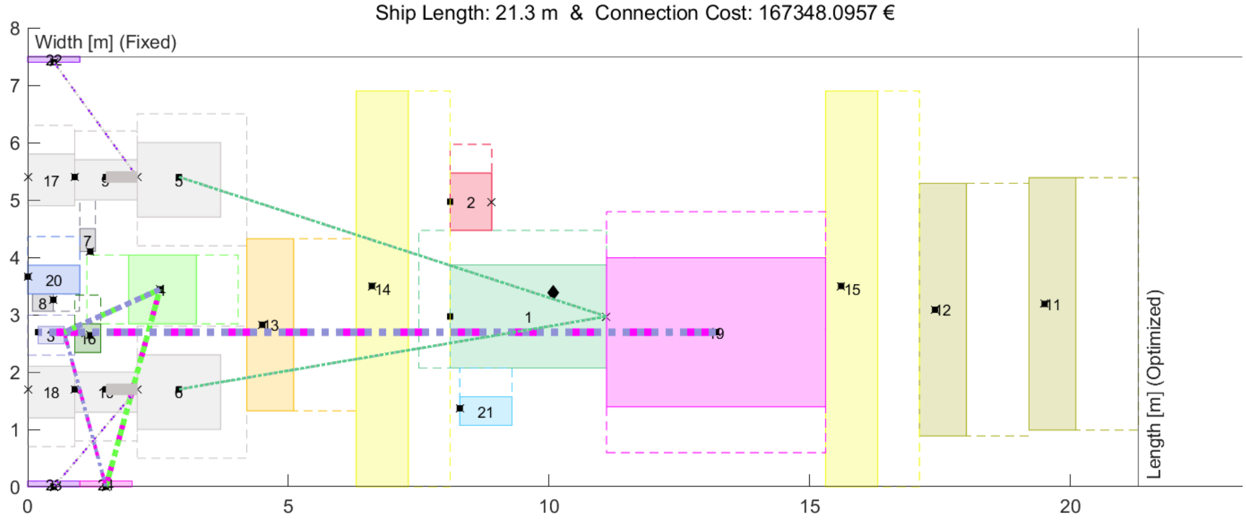
Solution No. 6

Ship Length: 21.3 m & Connection Cost: 189956.5908 €



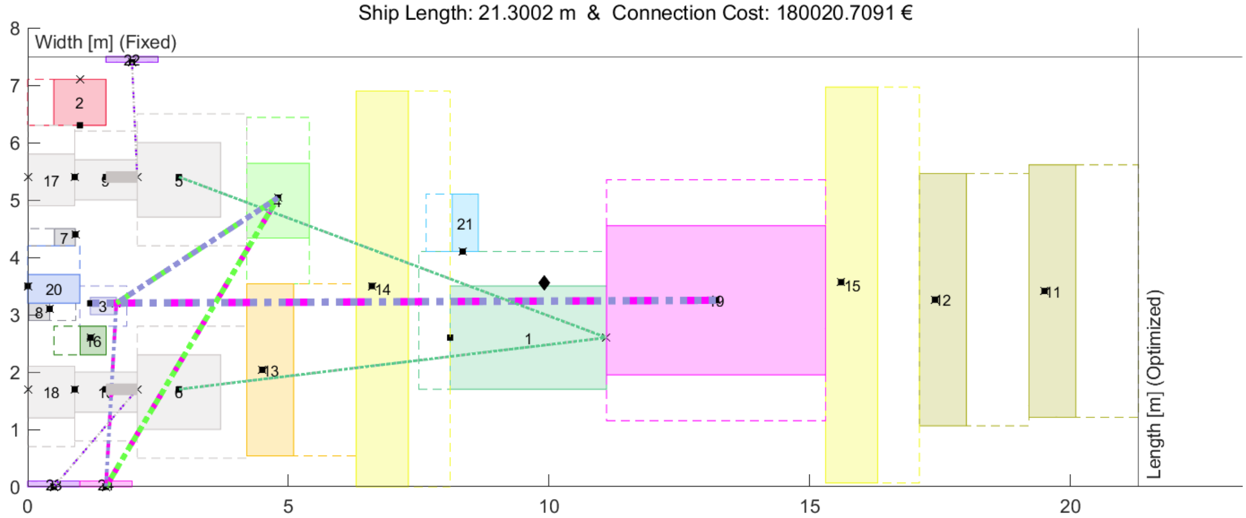
Solution No. 7

Ship Length: 21.3 m & Connection Cost: 167348.0957 €



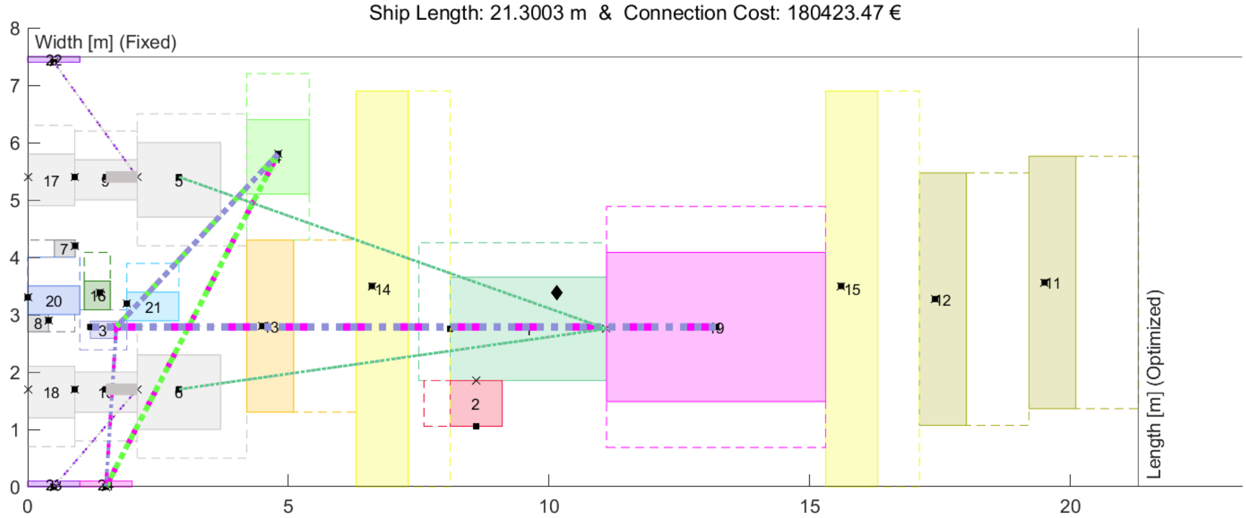
Solution No. 8

Ship Length: 21.3002 m & Connection Cost: 180020.7091 €



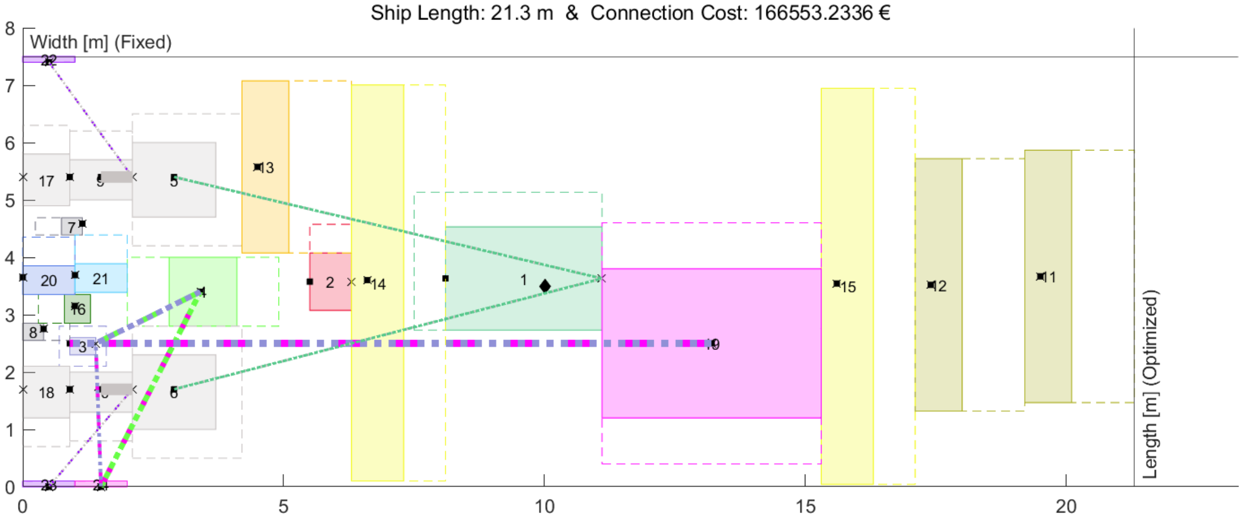
Solution No. 9

Ship Length: 21.3003 m & Connection Cost: 180423.47 €



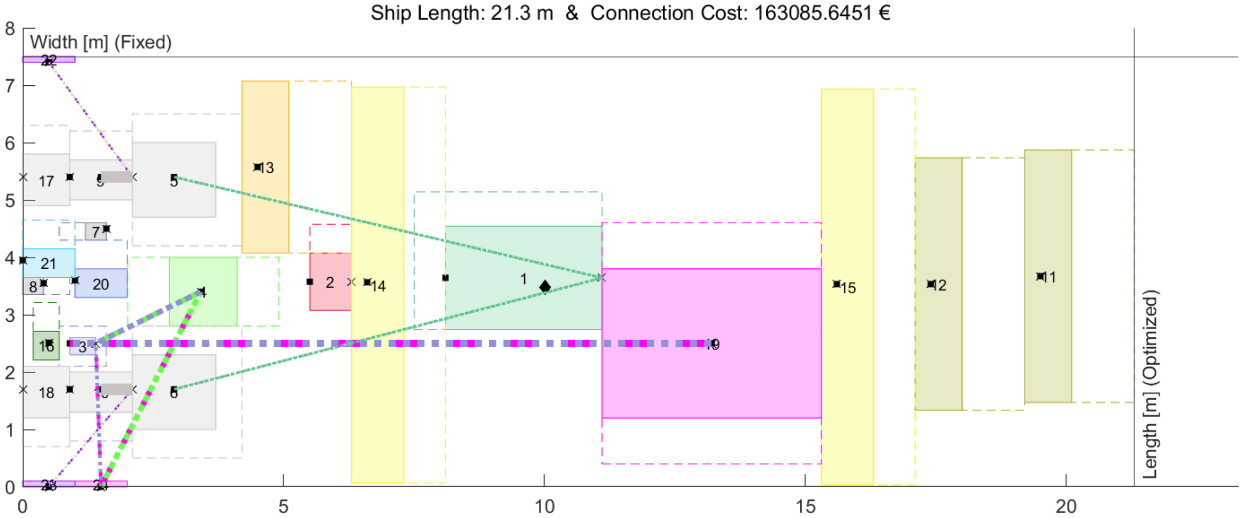
Solution No. 10

Ship Length: 21.3 m & Connection Cost: 166553.2336 €



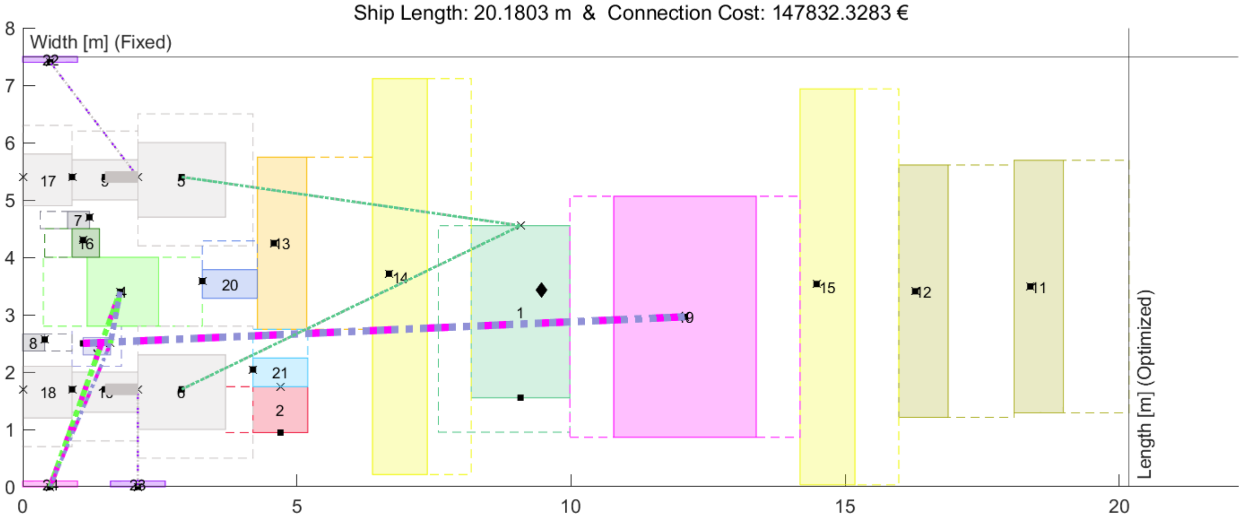
Solution No. 11

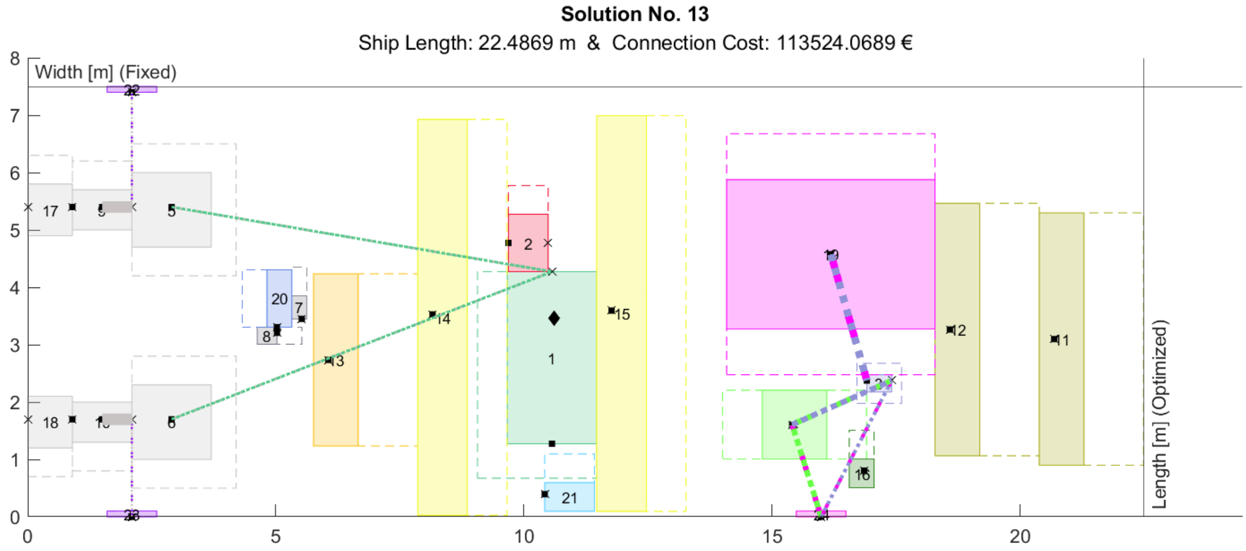
Ship Length: 21.3 m & Connection Cost: 163085.6451 €

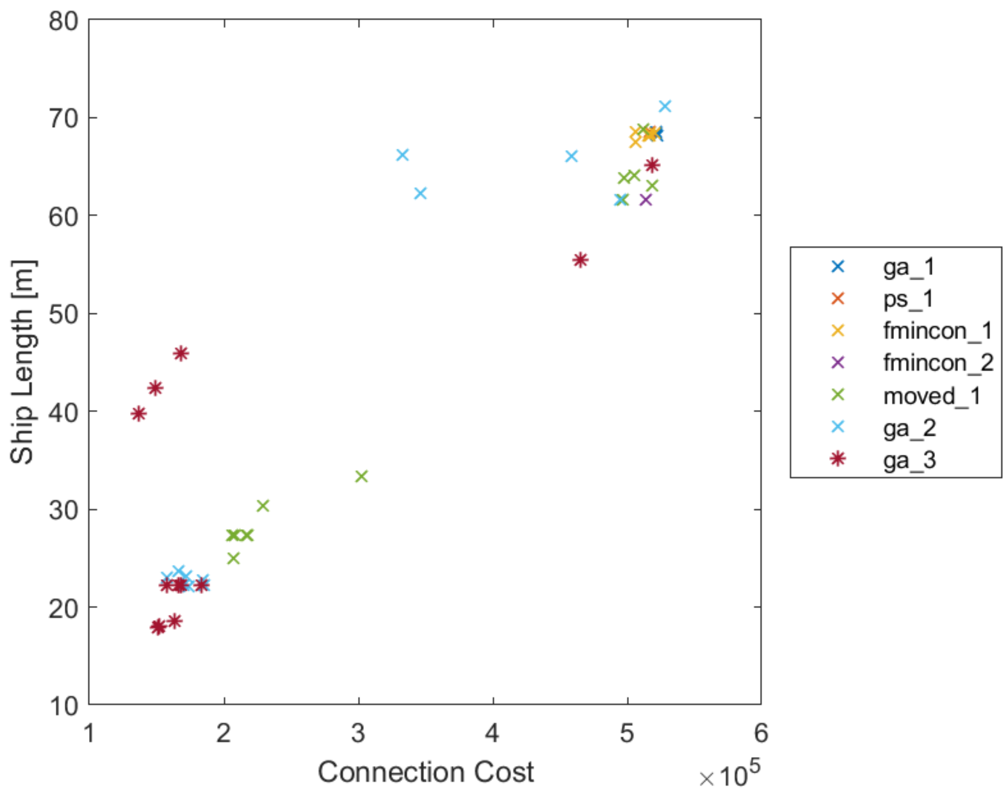


Solution No. 12

Ship Length: 20.1803 m & Connection Cost: 147832.3283 €

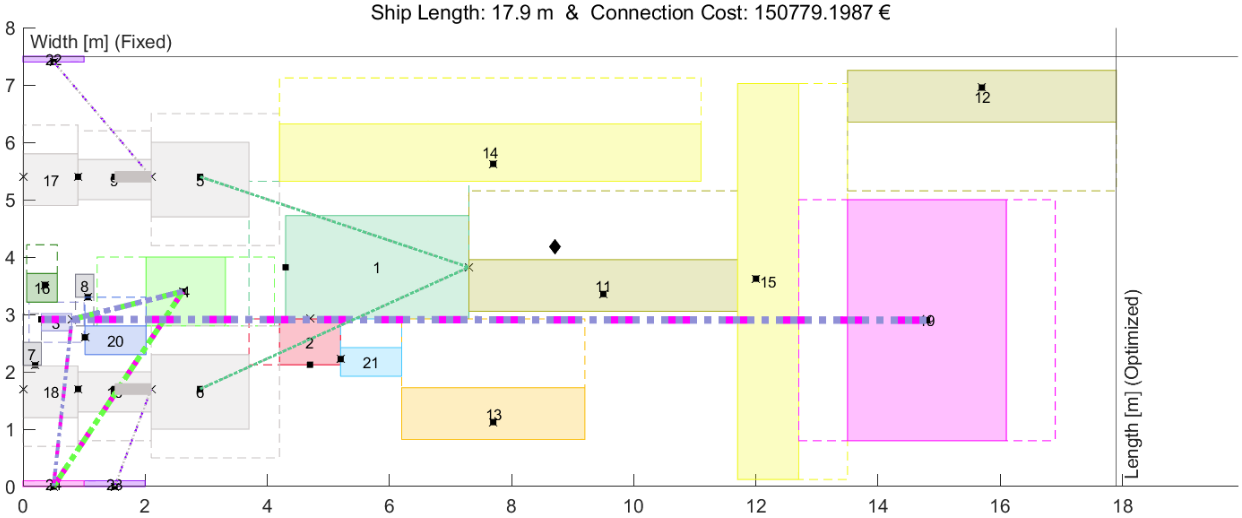



Solution No. 13
Ship Length: 22.4869 m & Connection Cost: 113524.0689 €
Width [m] (Fixed)
Length [m] (Optimized)


Ship Length [m]
Connection Cost
×10^5
ga_1
ps_1
fmincon_1
fmincon_2
moved_1
ga_2
ga_3

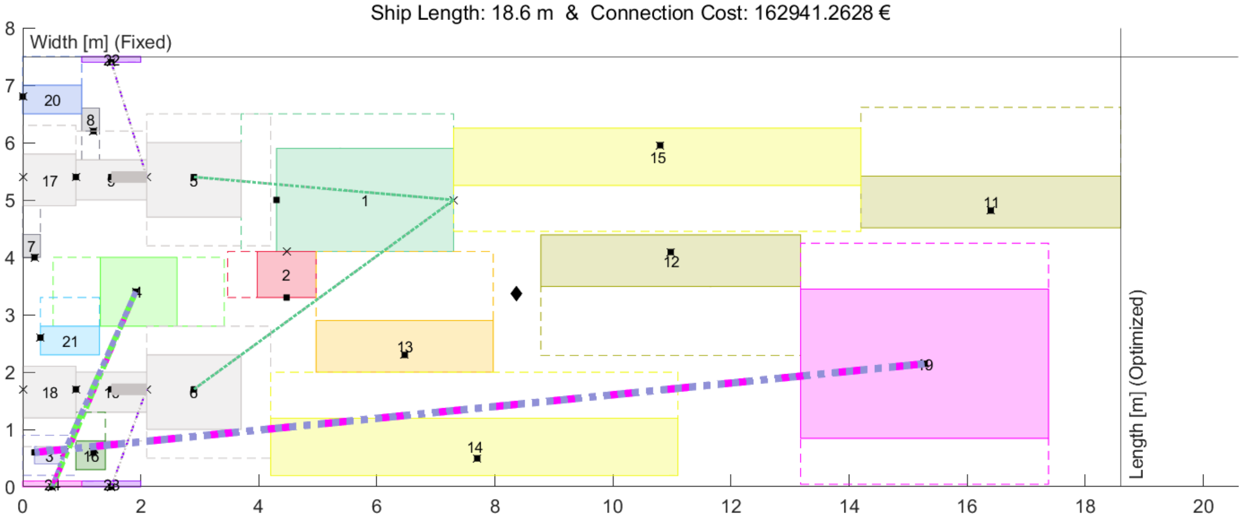
Solution No. 4

Ship Length: 17.9 m & Connection Cost: 150779.1987 €



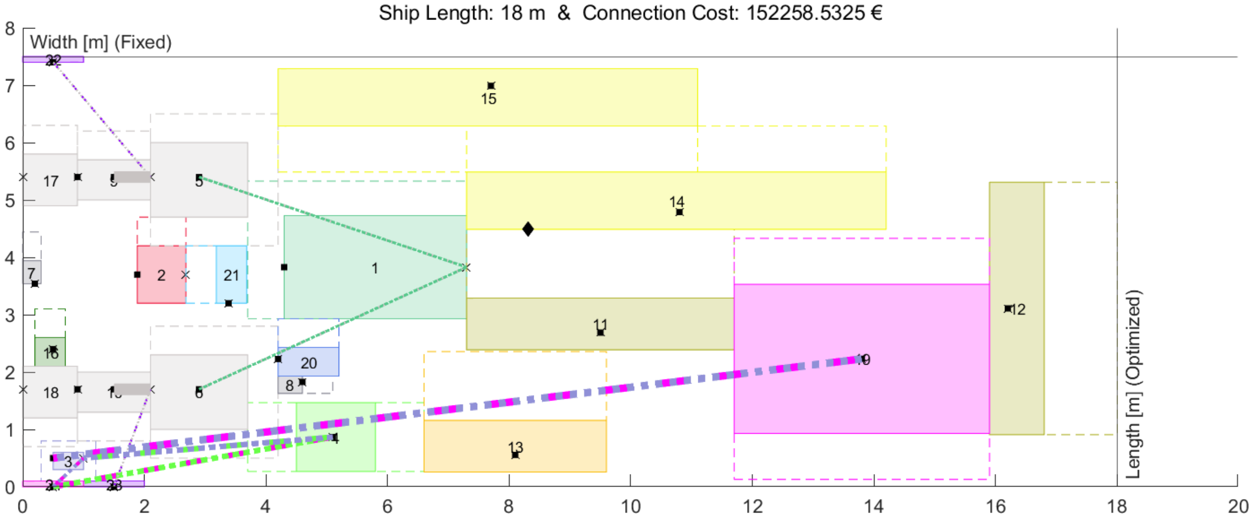
Solution No. 7

Ship Length: 18.6 m & Connection Cost: 162941.2628 €

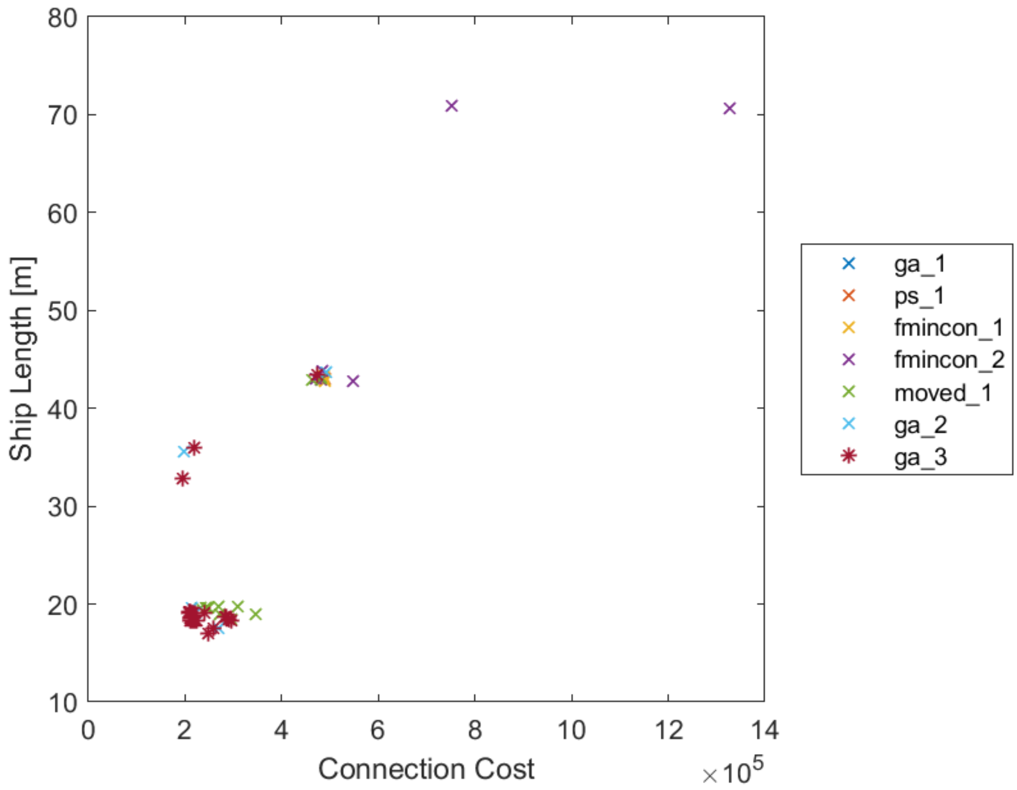


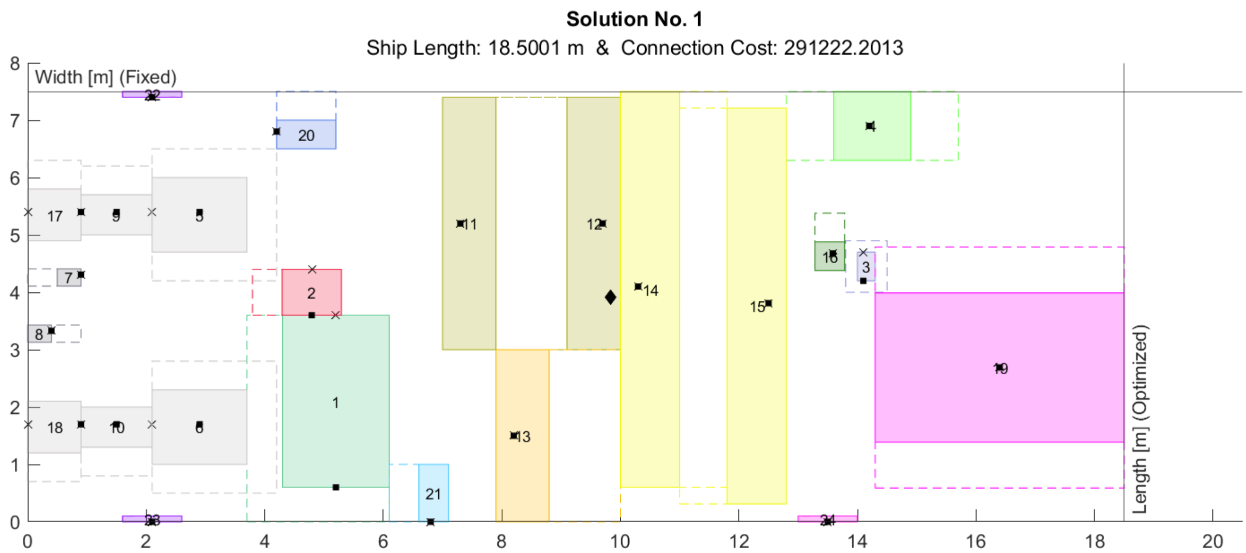
Solution No. 9

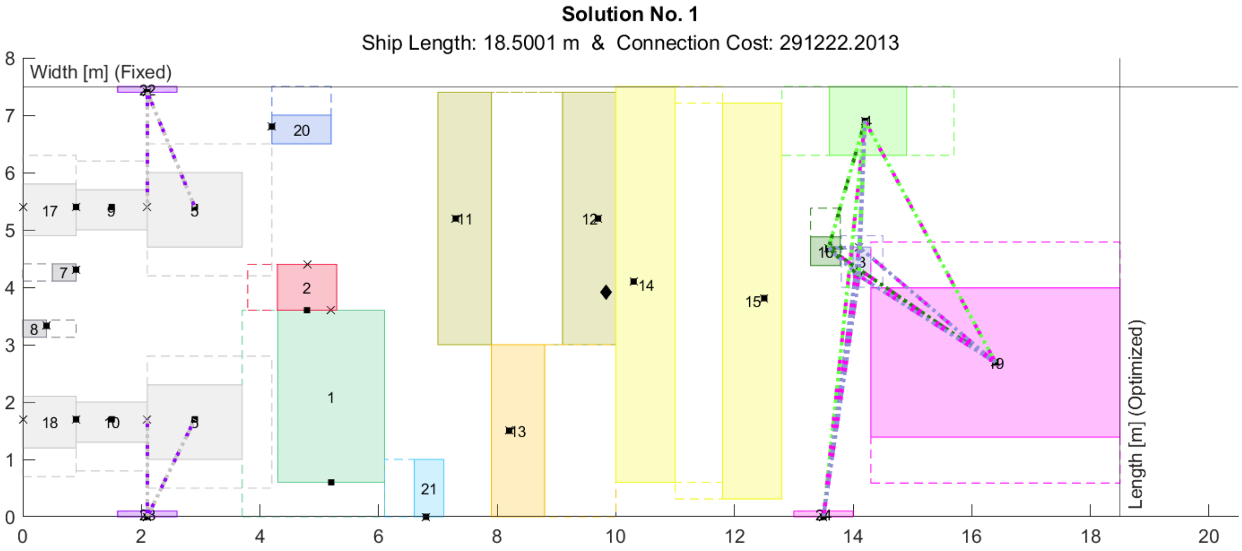
Ship Length: 18 m & Connection Cost: 152258.5325 €

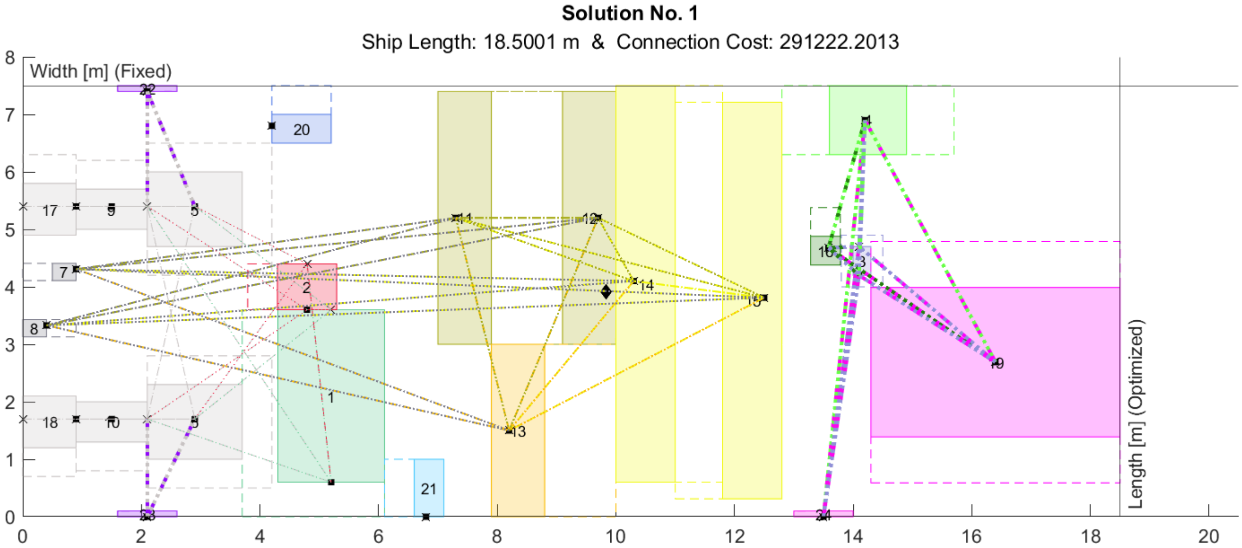


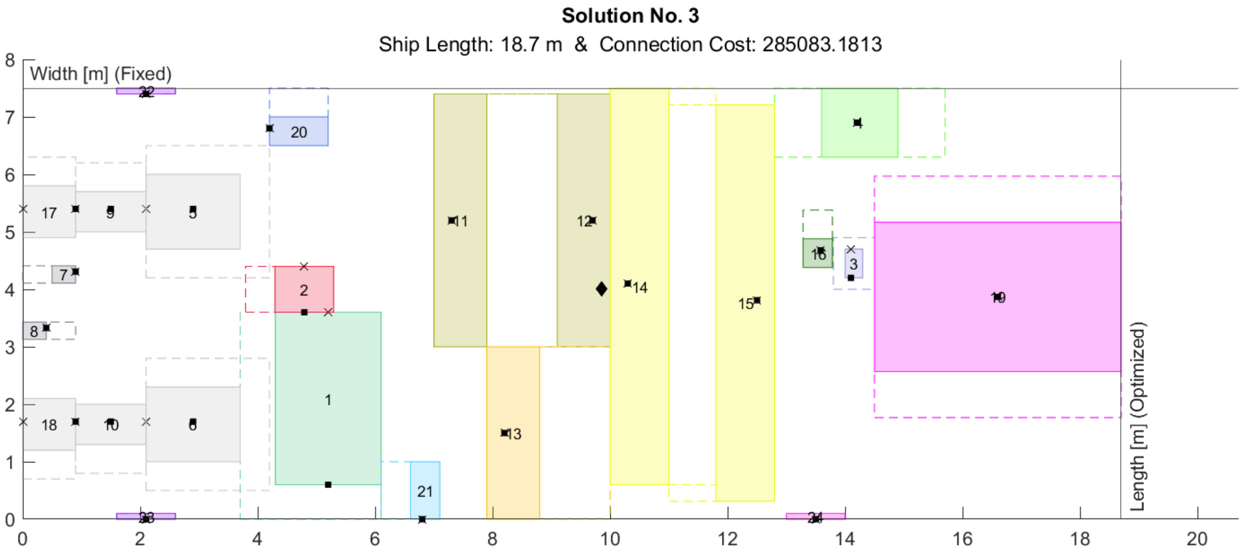
B.3. Relationship Matrix Tests



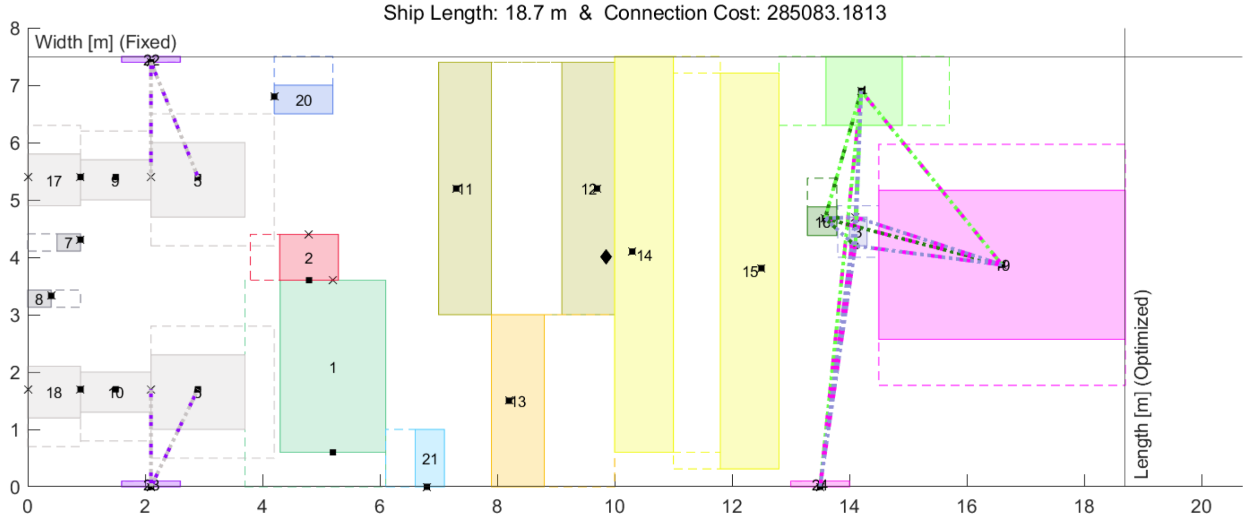



Solution No. 1
Ship Length: 18.5001 m & Connection Cost: 291222.2013
Width [m] (Fixed)
Length [m] (Optimized)

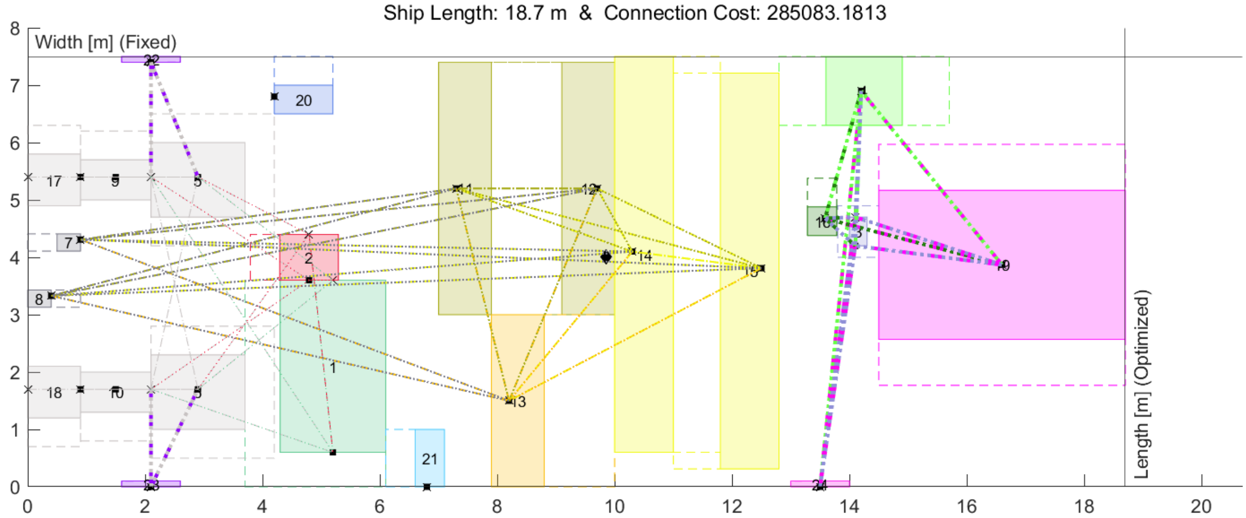

Solution No. 1
Ship Length: 18.5001 m & Connection Cost: 291222.2013
Width [m] (Fixed)
Length [m] (Optimized)


Solution No. 3
Ship Length: 18.7 m & Connection Cost: 285083.1813
Width [m] (Fixed)
Length [m] (Optimized)

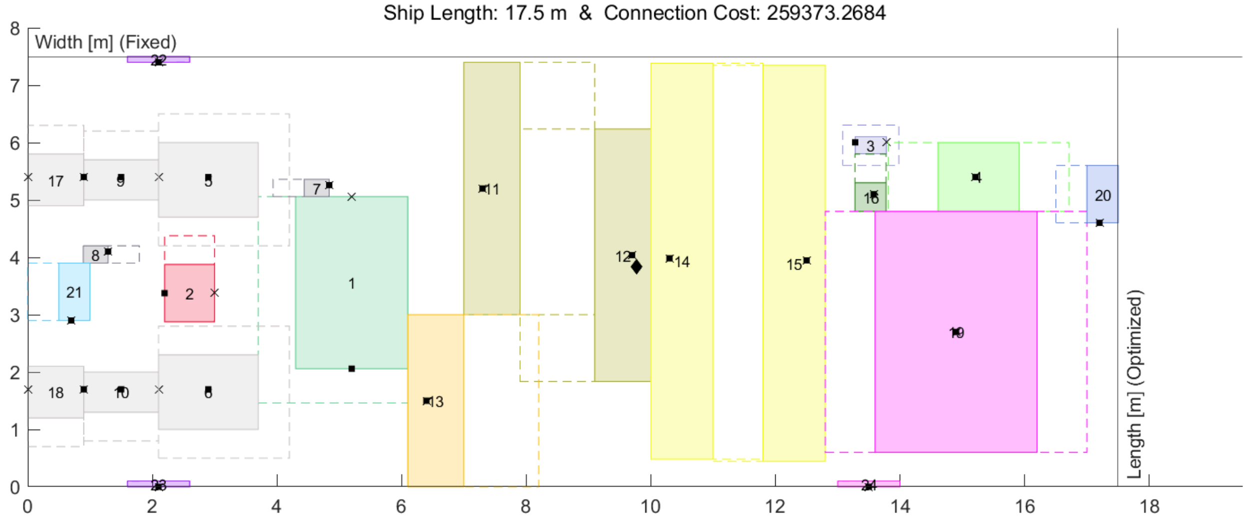
Solution No. 3
Ship Length: 18.7 m & Connection Cost: 285083.1813



Solution No. 3
Ship Length: 18.7 m & Connection Cost: 285083.1813

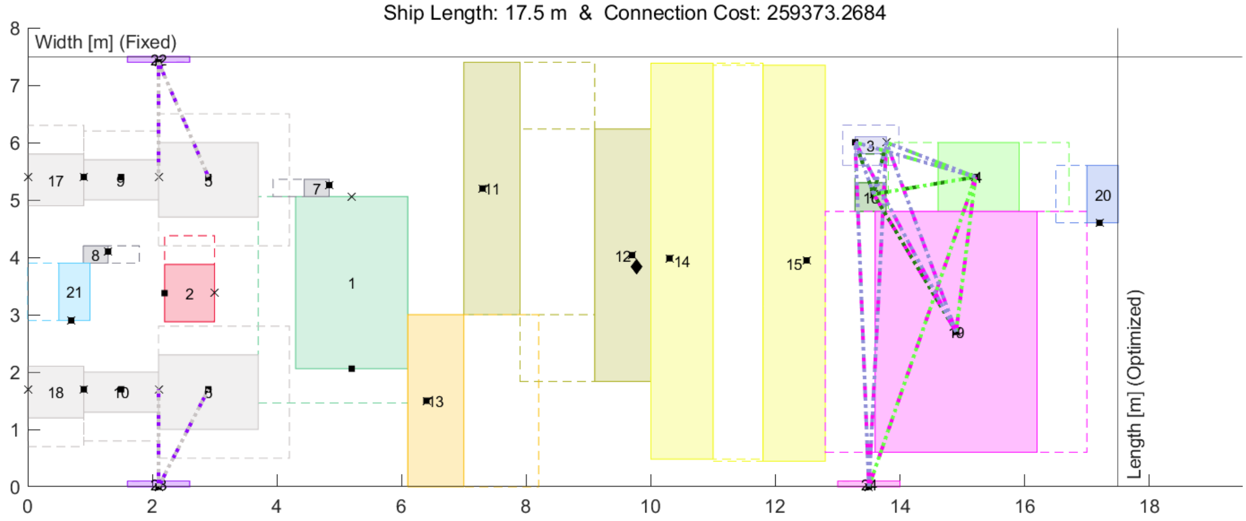


Solution No. 19
Ship Length: 17.5 m & Connection Cost: 259373.2684



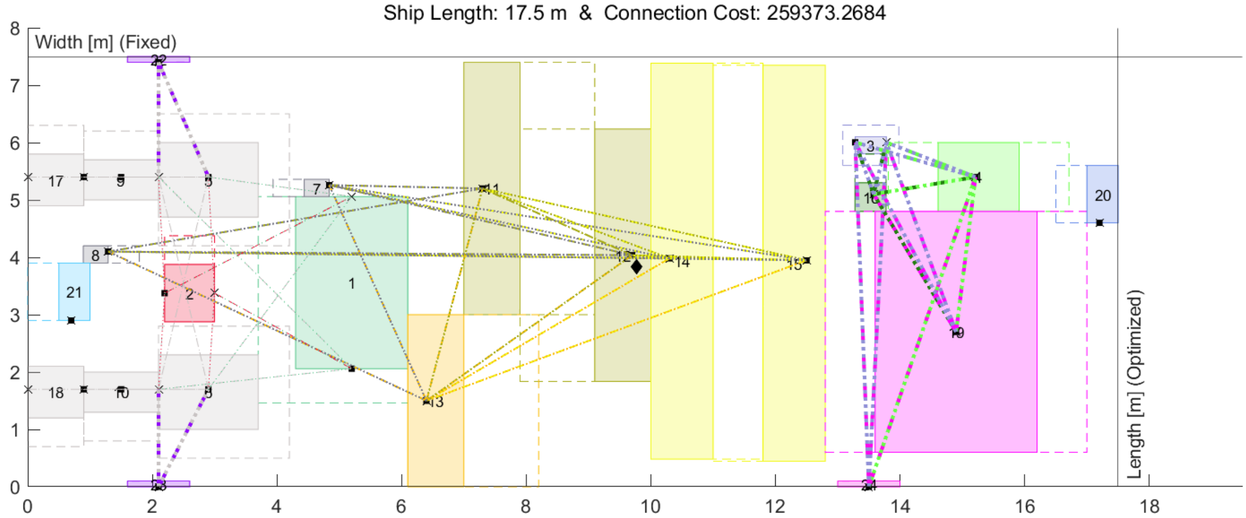
Solution No. 19

Ship Length: 17.5 m & Connection Cost: 259373.2684



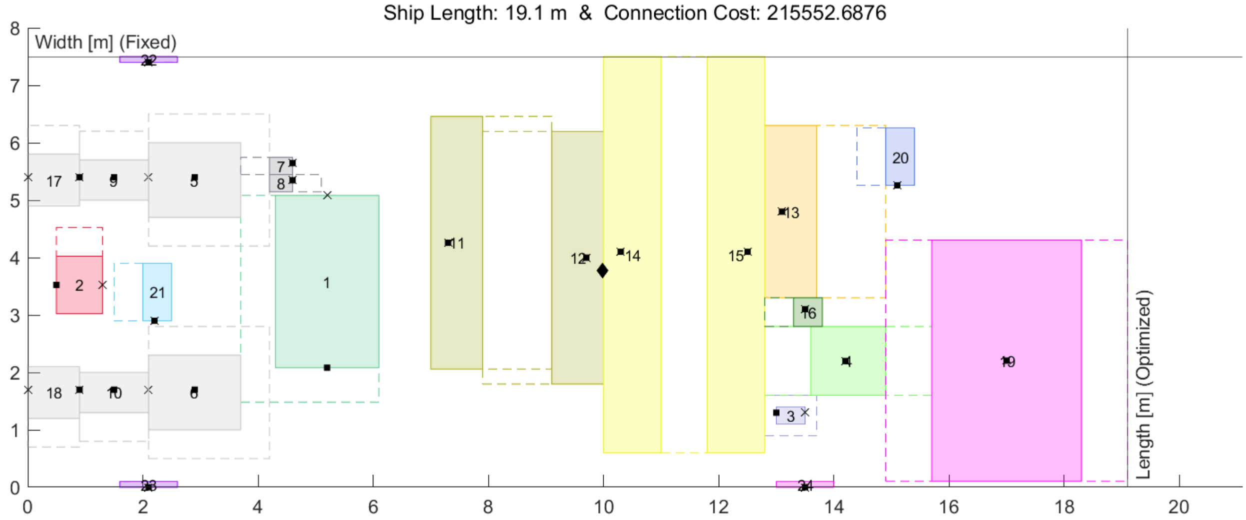
Solution No. 19

Ship Length: 17.5 m & Connection Cost: 259373.2684

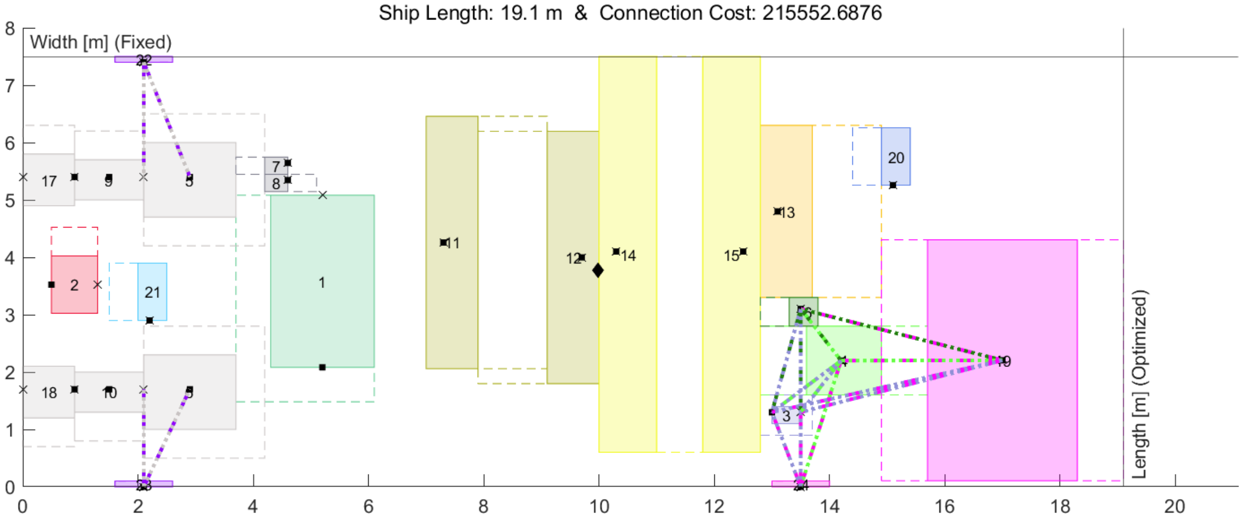


Solution No. 87

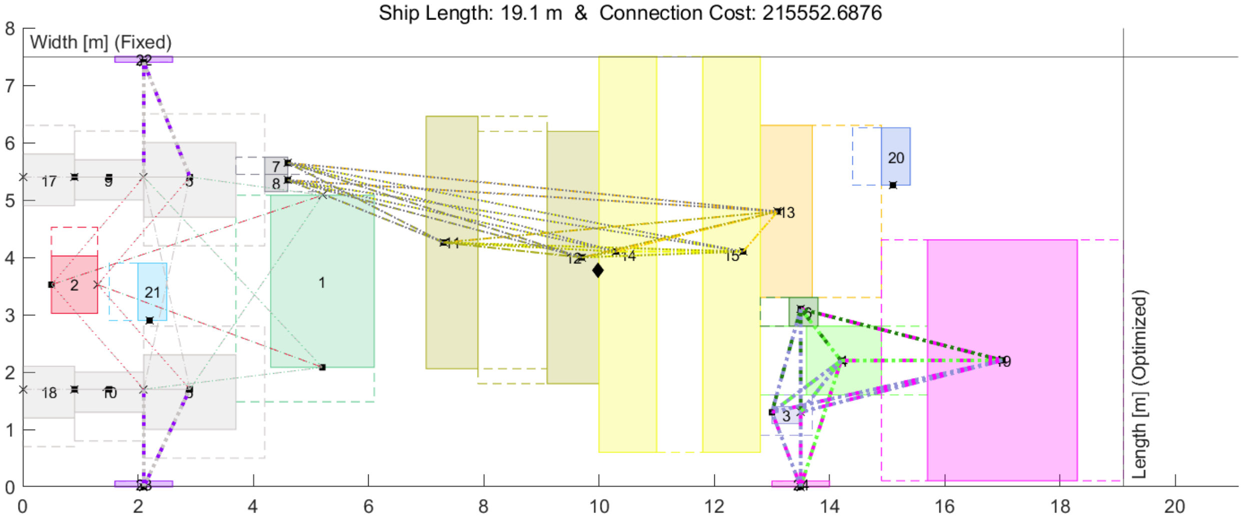
Ship Length: 19.1 m & Connection Cost: 215552.6876



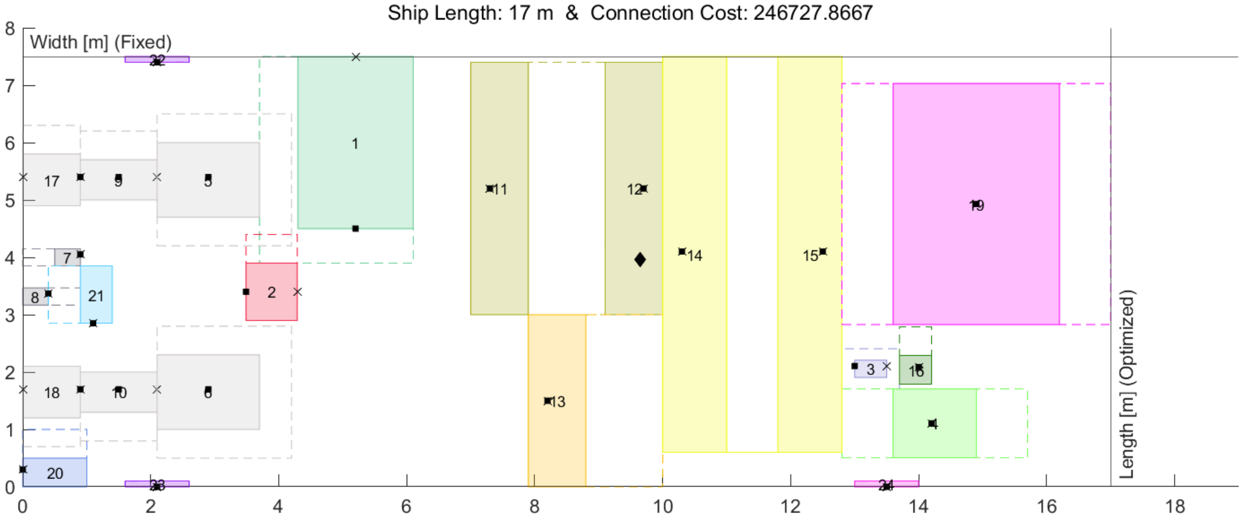
Solution No. 87
Ship Length: 19.1 m & Connection Cost: 215552.6876

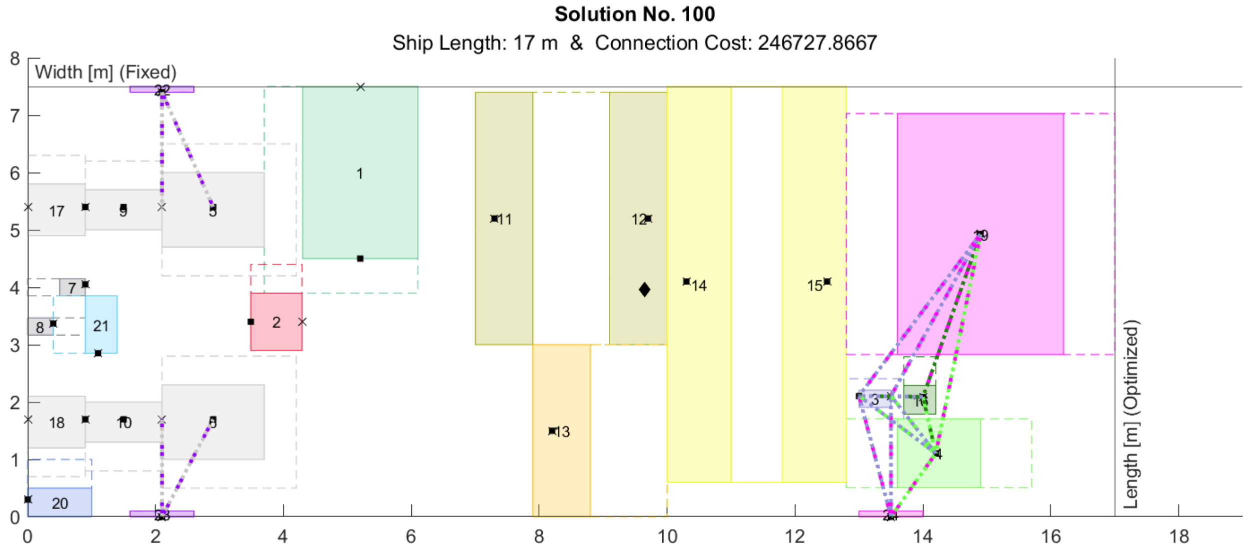


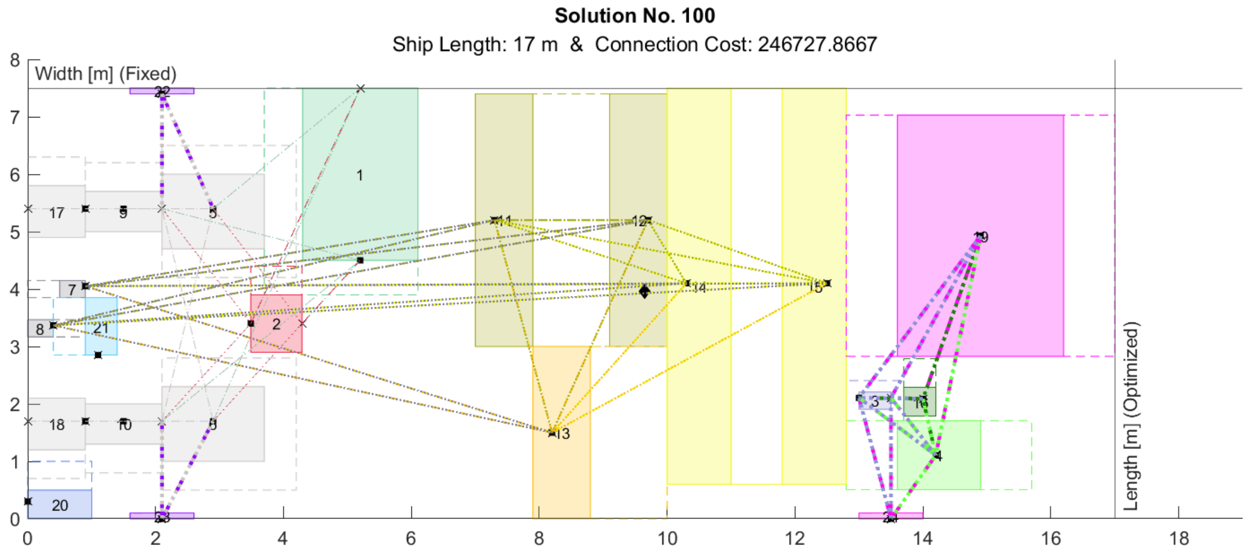
Solution No. 87
Ship Length: 19.1 m & Connection Cost: 215552.6876



Solution No. 100
Ship Length: 17 m & Connection Cost: 246727.8667




Solution No. 100
Ship Length: 17 m & Connection Cost: 246727.8667
Width [m] (Fixed)
Length [m] (Optimized)


Solution No. 100
Ship Length: 17 m & Connection Cost: 246727.8667
Width [m] (Fixed)
Length [m] (Optimized)