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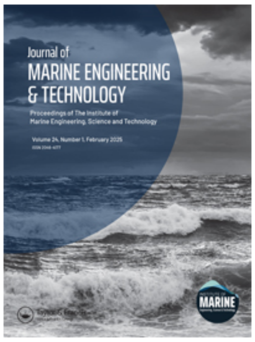

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Characterization of methanol power and energy systems' uncertainties and evaluation of their impact on layout design

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ABSTRACT

The integration of methanol power, propulsion and energy systems (PPE) generates uncertainties linked to the selection and sizing of systems, layout design and compliance with strict safety regulations. This paper argues that alternative fuels, such as methanol, should be treated as disruptive innovations, in part due to the uncertainties linked to their implementation. These uncertainties strongly connect to the PPE dimensions and the dependencies among the systems because of integration requirements. Through a model based system engineering inspired approach, the uncertainties are elucidated into relevant inputs for the proposed framework. The authors introduce an uncertainty evaluation framework that uses Monte Carlo simulations to generate the layout design space under uncertainty. The impact of uncertainty on the design is examined through a case study on the layout of a notional engine room. Multiple probability distributions for the PPE dimensions and varied logical architectures – reflecting systems dependencies – are applied to identify patterns in the generated design space. The varied logical architectures influence drastically the dominating solutions of the design space regarding the length. For a 1000-kW notional vessel, under the varied scenarios, the length of the engine room clustered in specific values while the connection costs produced wide value spectrum.

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Ship design; uncertainty propagation; systems integration; methanol power and energy systems

1. Introduction

The energy transition and the effort to decarbonize the shipping industry is an essential step toward addressing climate change, as the maritime industry accounts for approximately 3% of greenhouse gas (GHG) emissions (IMO 2021). Adopting alternative fuels can contribute drastically to mitigating emissions (IMO 2021). Methanol is one of the most promising alternative fuel options since it eliminates almost all SO_X and drastically reduces NO_X compared to conventional marine diesel (Zincir et al. 2023). The environmentally clean versions of methanol, biomethanol and e-methanol can be almost carbon neutral (Harmsen 2021; Zincir and Deniz 2021) and can be highly cost competitive in comparison to other alternative fuels (Korberg et al. 2021; Lagemann et al. 2022). However, transitioning is not without trouble, as Lindstad et al. (2021) demonstrated that the adoption of alternative fuels can lead to an energy consumption increase on a well-to-wake (WTW) basis between 100% and 200%. Additionally, the decreased energy densities of alternative fuels lead to an increased volume demand by a factor of 2.3 for methanol and 7.1 for liquid hydrogen (Ban and Bebić 2023). Thus new challenges arise in integrating new alternative fuels in the design of future vessels.

Various studies comparing alternatively fuelled power propulsion and energy systems (PPE) integration during the concept design phase have generated outcomes with significant variations regarding space requirements and impact on overall vessel size, despite the fact that these studies did not include uncertainty in their analysis (Green Maritime Methanol 2020; Streng et al. 2022; Zuidgeest 2022; Pothaar 2022; Ban and Bebić 2023). New challenges arise from alternative fuel integration due to storage and handling, vessel performance, space allocation, safety equipment and safe handling of the fuel (Ban and Bebić 2023). PPE systems such as fuel cells (FC) and batteries are still under development and their power and energy densities remain uncertain, as well as their lifecycle performance (EMSA and DNV 2021; Elkafas et al. 2022). One of the key issues that has currently been overlooked in the literature is how these technical uncertainties may better explain the future vessel size estimation discrepancies. Combined with the existing complexity of conceptual ship design (Rehn 2018), the need arises to understand the influence of the novel PPE systems on the design of the vessels as early as possible in the design process.

The aim of this study is thus to characterize the underlying uncertainties caused by PPE systems integration and propose a suitable uncertainty evaluation framework for their effects on layout. The proposed contributions of this paper are:

(1) Identifying the overlooked uncertainties linked to alternatively fuelled PPEs that cause design issues in the physical space of a vessel.
(2) A model based systems engineering (MBSE) inspired approach to structure the identified PPE uncertainties and trace them to the physical design space of the vessel.
(3) Development of an uncertainty evaluation framework to quantify the effect of alternative fuel PPEs to the design space of an engine room.

2. Problem formulation

PPE systems can be categorized based on de Vos et al. (2022) and Veldhuis et al. (2022). Influential uncertainties of PPE systems to

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incorporate for the methanol vessels design have been identified based on this system categorization.

- The *energy storage system (ESS)* describes the systems used to safely store and handle the fuel such as tanks, pipes and safety systems such as cofferdams.
- The *auxiliary systems* describe the systems used to generate electric power and auxiliary loads such as pumps and generators as well as the after-treatment systems for the necessary emissions mitigation.
- The *main propulsion engine power (MPE)* includes the engines used for the propulsion. The primary options are internal combustion engines (ICE), fuel cells (FC) and hybrid configurations including electric power generation and batteries.

Research gaps are identified via a literature review on methanol fuelled PPE systems, their configurations and the current design research on the integration of these systems.

2.1. Storage challenges due to methanol fuel properties

The properties of methanol fuel generate challenges for its storage and handling. Methanol is a low flashpoint fuel and is handled according to the interim guidelines of IMO's International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF) (ABS 2021; IMO 2022). This code leads to the requirement of cofferdams around the tanks, except for areas adjacent to the shell plating below the minimum waterline (ABS 2022). This leads to a considerable space demand that must be handled within the hull of the vessel.

The established IMO guidelines (IMO 2020) for methyl alcohol fuels are under constant review based on the knowledge gained through operation (Ellis 2016). Uncertainty regarding the extent of safety measures exists, as alternative designs could receive approval by proving the equivalent level of safety (Lloyds 2024). In terms of storage and handling, methanol shares more common traits with diesel fuel than LNG (see Table 1 Souflis-Rigas et al. 2023), as it is liquid and can thus be stored in conventional tanks (Andersson and Salazar 2015; Wang and Wright 2021). However, the low flashpoint of methanol ($\approx 11^{\circ}$C) means that it is extra flammable and the need for a protective area called cofferdams arises (ABS 2022; Bureau Veritas 2022). The cofferdams requirement, in combination with the lower energy density of methanol (Souflis-Rigas et al. 2023), makes the demand for fuel storage space more critical. Depending on the location the fuel tanks are placed, the size of the cofferdams varies (Bureau Veritas 2022; Zuidgeest 2022; Ban and Bebić 2023).

Pothaar et al. (2022) argued that for a diesel fuel capacity of 600 m^3, an equivalent 1300–1500 m^3 methanol fuel capacity is necessary, approximately 2–3 times the current volume. Kries (2021) showed that a 50% increase in the usable tank volume can be achieved by adopting a smaller cofferdam. The smaller cofferdam evaluation is a fair assumption considering that regulations are still under development for methanol.

Safety concerns also arise due to the toxicity and flammability of methanol (Karatuğ and Ejder 2023). Dangers of explosion can lead to an incident and compromise the integrity of the vessel (Hacker 2020). Methanol causes health hazard both for human skin and organs (van Rheenen et al. 2023), meaning that it cannot be placed adjacent to any manned or freely accessible space of the vessel for fire safety. These safety considerations to prevent fire risk and health hazards pose additional constraints to the layout of the systems within the vessel (Hacker 2020).

2.2. State-of-the-art of methanol fuelled PPE systems

Methanol can be integrated in a vessel using an internal combustion engine (ICE), FC or a hybrid set up. Souflis-Rigas et al. (2023) highlighted key advantages and disadvantages of ICE and FC as prime energy converters for methanol. Additionally, hybrid systems set a competitive option for reducing emissions through the electrification of propulsion and auxiliary system loads (Jianyun et al. 2019). This means that in addition to methanol PPEs, components for electrification need to be considered as potential sources of uncertainty. Table 1 provides an overview of the uncertainties in critical PPE components linking them to parameters that affect the physical design of the vessels such as the components' dimensions. The variety in FC technologies under development, such as solid oxide fuel cells (SOFCs) and proton exchange membrane fuel cells (PEMFCs), introduces uncertainty in their volumetric power density, thereby generating uncertainty regarding their sizing and dimensions (Souflis-Rigas et al. 2024).

Stapersma and de Vos (2015) showed that computing the dimensions of components integrated into the engine room, the analysis is more complex than just extracting dimensions from manufacturers' project guides. In combination with the fact that a dual fuel strategy requires tanks, fuel supply systems for both methanol and diesel and a voluminous aftertreatment system (Zincir and Deniz 2021), the size and shape of the PPEs become even more unclear, causing uncertainty regarding the actual layout arrangement of the PPEs.

Recent studies on the effect of alternatively fuelled PPE configurations on the size of navy vessels have provided inconsistent findings (see Table 2), both within a single study and between

Table 1. Justification of uncertainties in main PPE components.

Component	Uncertain parameter	Uncertainty justification	References
Methanol fuel preparation	Dimensions of required equipment	Risk based design can save space	Kries (2021) and Ban and Bebić (2023)
Diesel tanks	Dimensions of fuel tanks	Ratio of fuel used during combustion	Steiner (2024)
Methanol tanks	Dimensions of fuel tanks	Cofferdam size and actual capacity of installed fuel	Kries (2021)
Fuel cell	Volumetric, gravimetric power density, efficiency rate, degradation, consumption	Technological developments	Elkafas et al. (2022) and Van Veldhuizen et al. (2023)
Internal combustion engine	Volumetric, gravimetric power density, efficiency rate	Converter power density, combustion strategy	Zincir and Deniz (2021) and Van Veldhuizen et al. (2023)
Generator	Dimensions of component, volumetric, gravimetric power density	Technological developments Overdimensioning because of electrical load analysis	Prousalidis and Sofras (2016)
Electrical switchboard	Dimensions of component	Depending on the distribution technology selected (DC or AC), switchboard sizes vary. DC switchboards can be a more compact solution.	Geertsma et al. (2017) and Latorre et al. (2023)

Table 2. Effect of displacement of methanol fuelled PPE systems on navy vessels.

Propulsion configuration	Estimated Δ increase (%)	Design tool	References
Hybrid, ICE FC, Gas	18–25 %	Parametric tool	Pawling et al. (2022)
Hybrid, ICE Gas	1,4–20 %	Layout modelling	Pothaar (2022)
Hybrid, ICE FC, Gas	8–15 %	Parametric tool	Streng et al. (2022)

studies. One of the primary assumptions of Pawling et al. (2022) and Pothaar (2022) is that the additional weight by the integration of methanol fuelled systems does not lead to an increase in power demand. Snaathorst (2023) investigated the impact of alternative fuels integration to the size and consequently the resistance of various vessels that leads to increased power demand. The increase in size can vary from 2.4% to 6% depending on vessel type which leads to an additional power demand of 2.7% on average, which leads to further ambiguity for the results on Table 2

Lastly, a unanimous trend in conversions and retrofits to methanol is to first lengthen the vessel to generate additional space (Kries 2021; Snaathorst 2023; Pothaar 2022). This is rational as increasing the length can have a limited effect on the resistance (Liu and Papanikolaou 2019). However in most retrofit cases, they maintain the existing hull shape and explore alternative placement options for the additional methanol tanks (Harmsen 2021; Zuidgeest 2022; Pothaar 2022). This paper thus argues that:

- A portion of the PPE systems that need to be integrated into the vessel are still under development. Their development, and thus their performance, sizing and dimensions are still uncertain (see Table 1).
- The exact shapes and quantities of these components are unknown, as there are various possible PPE configurations.
- Studies evaluating alternative PPE configuration choices impact to overall vessel size (see Table 2) present large ambiguity, even though they overlook the aforementioned uncertainties and pick specific cases for the sizing of these components.

These points highlight the need to account for the overlooked uncertainties linked to PPEs when estimating their impact to the actual vessel.

2.3. State-of-the-art of the design of methanol fuelled ships

The dimensions of the PPE systems are largely influenced by the operational requirements set for the vessel. The intended range and sailing speed largely dictate the fuel consumption, required fuel storage space and the required installed power. As shown in Table 3 vessels with different missions and sailing speeds, but similar sizes, require highly different installed power. Considering that slow steaming and engine derating have proven to be effective measures for emission mitigation, there is a decrease in the installed power demand of some vessels (MAN 2022; Cariou 2011; Zincir and Deniz 2021). This affects the size of the machinery equipment and the overall size of the ship. The requirements regarding sailing speed and range may still be under discussion and thus uncertain during the design phase. Therefore, the design process should capture the relationship between these operational requirements for methanol PPE systems and the actual vessel design.

To date, research projects have primarily focused on to retrofits from diesel to methanol dual-fuelled vessels. These projects have mainly adopted a dual fuel 4-stroke engine and have essentially tried to fit in the extra tanks for methanol in the conversion process. Such a case is the Stena Germanica (Andersson and Salazar 2015; Portin 2015) that applied a new high-pressure common rail system, high-pressure pumps and the corresponding safety equipment. Consequently, the integration of many systems for methanol fuel preparation leads to large connection costs between the systems in the form of additional cable and pipe lengths (Portin 2015). If these systems' layout logic is wrong, it can lead to significantly unwanted connection costs. Thus the manner in which the systems are placed and the proximity between relevant systems have an influence on the size of the ESS and the engine room. Practically, the design options for integration of alternative PPE systems are limited when retrofitting to the predefined space of an existing vessel and can lead to compromises in the operational characteristics like the sailing speed (see Table 3).

Zuidgeest (2022) explored the general arrangement of an existing vessel and potential propulsion alternatives. Pothaar (2022) used a 3D modelling tool to evaluate the effect of methanol integration in reference to an existing ship. Ban and Bebić (2023) performed a hazard identification (HAZID) risk design approach to integrate the additional methanol tanks into the ballast tanks location with minimized effect. Green Maritime Methanol (2020) project investigated a variety of vessels, focusing on the placement of the extra fuel tanks and safety measures within an existing hull. The above-mentioned studies follow a sequential approach resembling the design spiral and only explore an existing design space to place the methanol tanks, meaning that the design choices are rather limited.

The use cases of GMM (Green Maritime Methanol 2020) have demonstrated that a retrofit can prove more complex and expensive, depending on the vessel type, size and the magnitude of the conversion (minor or major). For different vessel types, the sailing range was reduced by approximately 40%–50%, when integrating methanol (Green Maritime Methanol 2020; Pothaar 2022; Zuidgeest 2022). In contrast, Ban and Bebić (2023) found that the range for a 2-week mission remains almost identical. Consequently, the lack of a design method when retrofitting methanol PPE systems to vessels leads to unforeseen bottlenecks in the layout and operation of the vessel.

2.4. Requirements for an uncertainty evaluation framework for the layout of PPE systems

The proposed framework is necessary to integrate the uncertainty, as inconsistencies have been found regarding the size of the PPE systems, their arrangement rationale, their effect on the overall ship design, and vessel size. Unfortunately, many of these shortcomings

Table 3. Comparison of principal operational characteristics of methanol-fuelled vessels.

Vessel type	Vessel size (t)	Sailing speed (kn)	Installed power (kW)	References
Trail Sucction hopper dredger	DWT 4200	11	4600	Ban and Bebić (2023)
Stena Germanica ferry	GT 52000	22	24000	Portin (2015) and CruiseMapper (2023)
General Cargo vessel	DWT 7000	9.5	1600	Zuidgeest (2022)
Navy vessel	Δ 7200	18	50000	Pothaar (2022)
Cable laying vessel	DWT 8400	12.4	11000	Green Maritime Methanol (2020)

Note: [a]References in square brackets denote citations.

Table 4. Matching identified research challenges to method requirements.

Research challenges (RC)	Method requirements
[RC-1] Alternative fuelled PPE systems have uncertain sizing properties due to their on-going developments and variety of technologies	The method should develop a layout modelling tool that explicitly accounts for the relevant uncertainties
[RC-2] The PPE uncertainties relating to sizing can affect the vessel's layout, but have been overlooked by current studies	The method should quantify the impact of uncertainty in PPEs to physical shape, size of an engine room
[RC-3] Requirements for the integration of the systems (i.e. safety, electrification) generate dependencies that are overlooked when estimating the impact on vessel size	The method needs to account for dependencies among PPE systems and establish trends in their influence to the design space
[RC-4] There is a lack of a systematic design framework to structure the typically overlooked PPE uncertainties before designing the actual vessel	The method should use a systematic design framework to elucidate uncertainty factors into uncertainty modelling parameters
[RC-5] The effort to adopt alternative fuels by reducing range or speed leads to uncertainty regarding the actual required installed power and fuel tanks capacity	The method should allow for sensitivity study reflecting quantitatively on the machinery space sizing ambiguity because of ESS and MPE

only become obvious when designing the physical spaces of the vessel. The additional fuel storage space and the alternative PPE systems that are integrated into the engine room can cause these shortcomings. Further knowledge regarding technology development can lead to mitigation of the uncertainty regarding the sizing and dimensioning of the systems. Consequently, modelling the uncertainty of parameters related to these systems (e.g. dimensions) is a prominent requirement. To establish a suitable uncertainty evaluation framework, it is essential to match the main research challenges to method requirements (see Table 4).

Current design approaches for methanol vessels have overlooked the constant interaction between physical ship layout and the different system architectures (de Vos 2018). System architectures are tightly linked to requirements (i.e. the imposed regulations) for the integration of the systems. The framework should account for the linkages among different PPE systems and assess their influence on the final physical design of the vessel. One design method that shows great promise is model-based systems engineering (MBSE). Voth and Sturtevant (2022) highlighted the value of an MBSE framework by presenting its application to the modelling of power systems for navy vessels so as to decrease complexity in the systems' operation and selection process. Pfeifer et al. (2020) demonstrated that MBSE has the potential to capture dependencies between systems to trace the impact of possible design changes when developing a modular electric ferry production approach.

2.5. Value of model based systems engineering (MBSE) as a method to elucidate the uncertainties because of PPE systems into modelling parameters

Relevant studies have been evaluated to shape the proposed framework (see Table 5). The statements evaluated in Table 5 reflect the method requirements in Table 4. Brefort et al. (2018) developed an architectural framework for distributed systems and highlighted the value of considering three types of architectures (operational, logical, physical) to better capture their dependencies and understand their physical architecture. Dependencies among the specific systems for the electrification of a ferry were highlighted as a challenge that caused difficulty in modifying the physical design of the vessel (Pfeifer et al. 2020). In Table 5, the MBSE approach is only found at a basic level on the work of Rehn (2018) and on the application to PPEs integration of a hydrogen-fuelled vessel (Veldhuis et al. 2022). Essentially MBSE is the conversion of the conventional *document-based* systems engineering (SE) to *model based* and thus the integration of digital modelling environments in SE (Shevchenko 2020). The approach is based on the analysis of the design process into four main layers inspired by systems engineering (SE) (Kossiakoff et al. 1991).

- *Operational Analysis* represents the basic requirements set for the operation of the vessel are established.
- *Functional Requirements* define the functions expected to be fulfilled by the system.
- *Logical Architecture* defines the system technologies that are used to fulfil the requirements and their possible interconnections to comply with different regulations requirements (Veldhuis et al. 2022).
- *Physical Architecture* defines the actual placement of the systems in the physical space (e.g. with a general arrangement plan).

MBSE can capture with system architecture the decomposition into subsystems (Madni et al. 2023). Shields et al. (2017) modelled the effect of functional requirements on the layout of distribution systems and proved the relationship between logical architecture and physical architecture influences the vessel design holistically. Datta et al. (2022) showed that software-based uncertainty analysis methods facilitate the scenario exploration, when dealing with ill-defined requirements, like the thrust requirements for an aircraft. MBSE is incorporated into this research as the method to structure a suitable uncertainty quantification tool for layout.

Table 5 highlighted the amount of diverse factors that have not yet been integrated into a unified design framework. Table 6 allocates the identified uncertainties to the relative MBSE layers. This

Table 5. Evaluation of relevant literature against the proposed method requirements.

Traceability of changes	Systematic design method	Uncertainty modelling	Layout integration	Approach name	References
X	X	X	✓	Design parametric tool	Kries (2021)
X	X	X	✓	Design spiral for retrofit	Green Maritime Methanol (2020)
✓	✓	✓	X	SE design under uncertainty	Rehn (2018)
✓	✓	X	X	MBSE for design and integration of systems in a vessel	Brefort et al. (2018), Pfeifer et al. (2020), and Voth and Sturtevant (2022)
✓	✓	X	✓	PPE system design with MBSE	Veldhuis et al. (2022)
X	X	X	✓	Machinery layout tool	van der Bles (2019) and Poullis (2022)
✓	✓	✓	✓	Uncertainty evaluation framework for layouts	Souflis-Rigas et al. (2023)

Table 6. Identified uncertainties allocated to corresponding MBSE layers.

MBSE layer	Uncertainty
Operational analysis	Range, speed
Functional requirements	Safety measures required
Logical architecture	System architecture, topology, dependencies between systems
Physical architecture	Dimensions and amount of selected PPE systems

categorization attempts to highlight that requirements from different levels trace back to uncertainty in the physical space.

Monte Carlo (MC) has been pointed out as commonly used tool to model uncertainty within a design framework (Madni et al. 2023). Souflis-Rigas et al. (2023) highlighted through various applications that MC is an effective and straightforward simulation-based method for exploring the influence of stochastic inputs on model outputs. This study aims to propagate the uncertainties found within the functional requirements, logical architecture and physical architecture layers (see Table 6) and the dimensions of the individual components to the overall engine room size and arrangement leading to an initial indicator for ship vessel size. This paper focuses on the integration of uncertainty within the physical architecture layer while considering variations in the logical architecture and their effect on the engine room layout and length.

3. Proposed uncertainty evaluation framework for layout

The proposed framework is illustrated in Figure 1 and is constituted of three main components:

- Inputs
- Monte Carlo simulations using the Layout generator
- Statistical analysis for the MC simulation outputs.

In Figure 1, the blue boxes indicate deterministic parameters that receive one exact value. Green boxes indicate the parts of framework that can receive a distribution of values and are part of the MC. The layout generation algorithm was built based on Poullis (2022) has been integrated into a Monte Carlo simulation (MC). MC is used to quantify the impact of uncertainty in the size and logical architecture of the integrated PPEs to the layout of an engine room.

3.1. Inputs

Based on the initial formulation by Poullis (2022), the model is provided with the necessary parameters to produce solution. The bounds for the decision variables of the facility layout problem (FLP) and the parameters to model the boxes (inputs, outputs margins) are defined determistically for the layout generator. The length and width of the building blocks (BBs) PPEs as well as the connection matrix (CM) are the parameters introducing the uncertainty to the model (see green box in Figure 1). For each MC simulation, their values are sampled from a distribution of values to complete the inputs for the layout generator. Their effect to the distribution of the model objectives should be evaluated to understand design impact.

Using this framework, the design space is explored probabilistically to gain an understanding of the influence of different PPE systems physical dimensions (length, width) on the overall length and connection costs of a notional engine room.

3.2. Monte Carlo simulations using the layout generator

Layout generator serves as the simulator for MC and therefore is a key component of the framework. The layout generator is based on solving the unequal area FLP, used by Poullis (2022) to model the shipboard layout of a machinery space. The classic FLP generates arrangement of units (BBs in this case) in a plant area to attain the most effective layout that minimizes the connection cost objective without the BBs overlapping (Anjos and Vieira 2017). In the model proposed by Poullis (2022), and extended in this paper, the FLP is framed as a multi-objective problem with non-linear constraints. The *objectives* of the problem are the minimization of *length* and *connection costs*. The BBs are modelled as nested boxes within the layout algorithm as depicted in Figure 2. The inner box illustrates the actual size of the component and the outer box depicts that account for margins corresponding to specifications for components, applied safety measures according to regulations and expert inputs (Poullis 2022). They have an input and output point to compute more accurately the connection points that pipes and cables may be connected. The second objective: minimum length is computed by finding the rightmost BB x-coordinate and adding either length or width depending on the orientation of the BB. Each BB has a set of three decision variables: x-coordinate, y-coordinate and rotational freedom. Rotational freedom is equal to 1 if it is allowed to rotate by 90° and 0 for non-rotation. A coordinate-based system is used for the layout generation, meaning that decision variables x,y are the coordinates on the bottom left corner of the BB.

Connection costs (CCs) refer to the various connections such as pipe routing and cable links that need to be implemented to connect the various PPE systems. The CCs are based on computing the rectilinear distances between the various systems and multiplying with the corresponding cost factor (Equation 1) (van der Bles 2019). The cost of each connection between BBs is provided using the connection matrix (CM).

$$Obj_1 = \min \sum_{i=1}^{N} \sum_{j=1}^{N} CM_{ij} \cdot d_{ij}$$
$$= \min \sum_{i=1}^{N} \sum_{j=1}^{N} CM_{ij} \cdot (\mid x_{i_{out}} - x_{j_{in}} \mid + \mid y_{i_{out}} - y_{j_{in}} \mid) \quad (1)$$

The multi-objective optimization is implemented using Deb's NSGA-II (Deb 2011) incorporated into the MATLAB global optimization toolbox (MATLAB 2024). Table 7 lists the critical parameters to define the optimization process. The population size is set to 400 by trial and error, so as to compromise between execution time and layout solution accuracy. To reduce the computational cost, the GA algorithm terminates if the j_{th} solution does not improve more than 1% in comparison to the ($j_{th} - 1$) (see Equation 2 and Figure 1).

FLP is an NP-hard problem, meaning that computational complexity increases, as the units increase (Anjos and Vieira 2017). To be able to test a variety of scenarios in MC, the proposed framework generates layouts for a simplified engine room with a fixed width of 6.5 m. 6 BBs are selected for this case study. Therefore this case study has 18 decision variables ($n_{variables}$).

$$|Obj_{j,i} - Obj_{j,i-1}| \leq 0.01, \quad j = 1,2 \quad (2)$$

The convergence criterion (Equation 2), regarding the values of the objectives, length and connection costs, is applied to reduce computational time when the GA cannot provide fundamental layout improvements. GA produces multiple solutions per set of inputs. The maximum value of the objectives out of these solutions per MC run has been used to normalize the objective values in Equation (3) and thus receive values in the range of 0–1. Each set of inputs (dimensions and connection matrices) needs to match one layout output to generate a distribution of engine room length and connection costs outputs

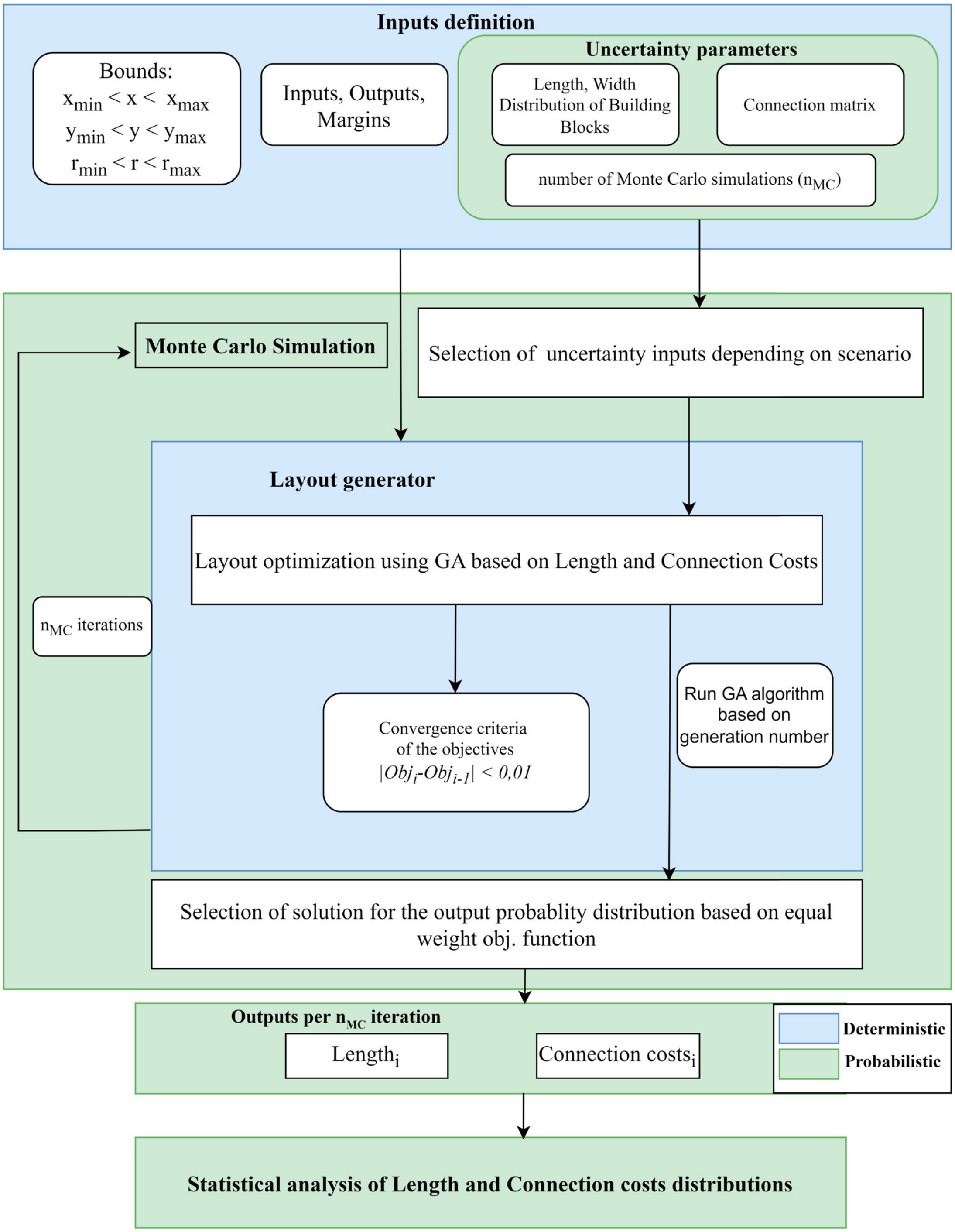

Figure 1. Proposed uncertainty evaluation framework architecture.

within the MC simulation. Thus the influence of variable dimensions on the overall size of the engine room can be observed. Therefore, the selection Equation (3) is applied, which allocates equal weight factors to the objectives of the problem:

$$\min Obj = \min\left(\sum_{i=1}^{2} 0.5 \cdot \frac{Obj_i}{\max Obj_i}\right) \tag{3}$$

The GA output that minimizes the value of Equation (3) is integrated into the MC simulation output. For each n_{MC} simulation, equal weight factors have been assigned to the objectives of the problem and the objectives are normalized by dividing each with its respective maximum value and receive values ranging from 0 to 1 .

3.3. Statistical analysis

The output distributions of length and connection costs are analysed using the visualization and computation of statistical metrics to identify trends and compare the different scenarios applied to the problem. The data are visualized using scatter plots, histograms, box plots:

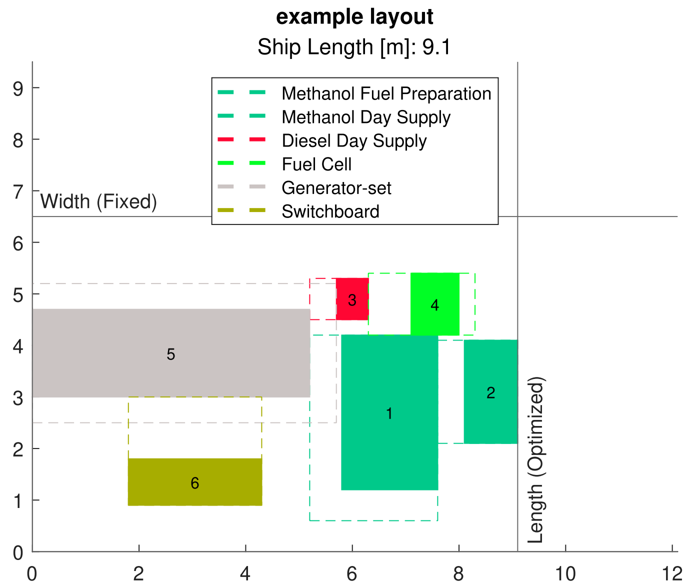

Figure 2. Example layout having as input the baseline logical architecture and dimensions from uniform distribution.

Table 7. GA parameters definition, $n_{variables}$ refers to the number of decision variables.

Parameter	Value
Population	400
Maximum Generations	$200 \cdot n_{variables}$
Maximum Stall Generations	100

- The scatter plot (e.g. Figure 4) illustrates the design space of solutions and provides an insight into the relationship between the two objectives.
- The histogram (e.g. Figure 5) provides insights into data density, distribution shape, skewness and value spread.
- Thebox plot (e.g. Figure 6) shows the median as a red line, quartiles as the box edges and outliers as red points outside the whiskers. Outliers are data beyond 2.7 standard deviations. Box plots are effective for comparing different scenarios in the case study and understanding central tendency, skewness and outlier points.

The analysis focuses on calculating the main statistical metrics describing the distribution shape and plotting them in histograms, box plots and scatter plots to gain a qualitative understanding of the generated design space for the engine room size and the connection costs. This analysis aims to identify possible peculiarities occurring in the state space of the solutions. The effect of scenarios to the design space is quantified using statistical measures for the objectives (length, connection costs) of the optimization problem.

4. Case study

4.1. Notional case study vessel

To test the proposed framework, a case study has been developed representing the main components of a notional hybrid methanol-fuelled yacht with installed power $P_{propulsion}$ of 1000 kW, based on Steiner (2024). To simplify this case study, only key components are included. The simplification is made to increase the reliability of the generated design space by the GA and decrease the computational complexity across the MC simulations (see Section 3.2).

The layouts generated in Souflis-Rigas et al. (2023) always placed the ICE and the Generator together and therefore in this case study we considered them as one unit called: Generator-set. Six main BBs representing an engine room were selected and Table 8 presents their reference dimensions according to relevant literature. Figure 2 illustrates an indicative layout of the engine room for the selected BBs.

A 10% uncertainty margin is applied to the reference dimensions found in Table 8, which produces the uncertainty dimensions interval columns that serve as the lower and upper limits for the MC inputs distributions. The justification for considering these uncertainty intervals is provided in Table 1.

$$CM_{baseline} = \begin{bmatrix} 0 & 2 & 1 & 2 & 2 & 1 \\ 2 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 \\ 2 & 0 & 0 & 0 & 0 & 1 \\ 2 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 1 & 0 \end{bmatrix} \quad (4)$$

The connection matrix, $CM_{baseline}$ (see Equation 4), expresses the importance of the connection between different components, with 0 denoting a connection of minimum importance and a 4 denoting a highly important connection and thus components should be in close proximity together (see Poullis 2022 for detailed definition of connections). The weight values assigned to $CM_{baseline}$ ranged from 1 to 2, signifying existing connections without imposing strict BBs dependencies on the layout generator.

$$\mathrm{CID}_i = \frac{\sum_{n=1}^{i} \mu_{Objective(i)} - \sum_{n=1}^{i} \mu_{Oblective(i-1)}}{i} \quad (5)$$

Before exploring the results, the convergence of the MCs was determined. 1% was deemed sufficient convergence to match the accuracy of the GA convergence (see Equation 2). The cumulative incremental difference (CID) defined in Equation (5) expresses the change of the cumulative mean value (μ) of length and connection cost respectively from i_{th}-1 to i_{th} MC simulation, divided by the total simulation runs (i). CID was computed for 500 simulation runs in Figure 3 and yielded acceptable convergence for both objectives.

Table 8. Dimension ranges of the engine room PPE components inspired for a notional vessel of 1000 kW (800 kW dual fuel Methanol generator set and 200 kW FC).

	Uncertain dimensions interval [m]		Reference dimensions [m]		
Building block	Width	Length	Width	Length	References
Methanol fuel preparation [1]	1.62–1.98	2.7–3.3	1.8	3	Poullis (2022)
Methanol day supply [2]	0.9–1.1	1.8–2.2	1	2	Steiner (2024)
Diesel day supply [3]	0.54–0.66	0.72–0.88	0.6	0.8	Steiner (2024)
Fuel Cell [4]	0.81–0.99	1.08–1.32	0.9	1.2	Ballard (2024)
Generator-set [5]	1.53–1.87	4.77–5.83	1.7	5.3	Wärtsilä (2024)
Electrical switchboard [6]	0.81–0.99	2.34 –2.86	0.9	2.6	ABB (2011) and Steiner (2024)

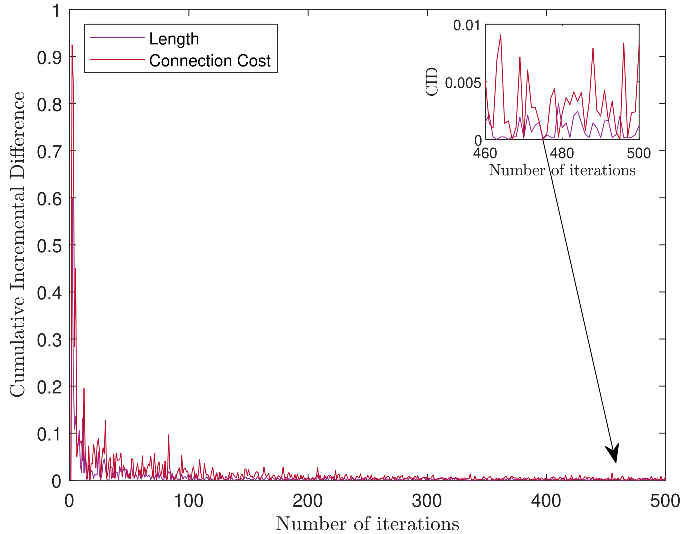

Figure 3. Convergence of the Monte Carlo simulation for the two model output variables for uniform distribution. The zoom in shows that both model objectives have converged to values less than 0.1.

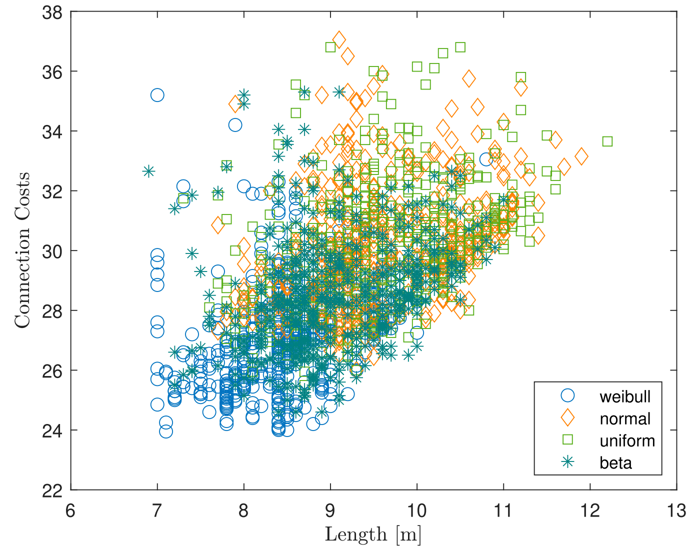

Figure 4. Scatter plot depicting the MC solution space when applying the four test distributions.

For the case study, three scenarios are examined:

(1) Impact of uncertain BB dimensions with a fixed logical architecture
(2) Impact of varied logical architecture with fixed BB dimensions
(3) Impact of uncertain logical architectures and variable BB dimensions.

4.2. Effect of uncertain BB dimensions

This study aims to extend and further validate the results and conclusions in Souflis-Rigas et al. (2023). Initially, the authors applied a uniform distribution because of the equal likelihood assigned to each input value. However, the unknown technological development of PPEs may lead to different distribution types for their dimensions. The selected distribution types (see Table 9), generated samples with different probability density for the input values. The possible combinations of inputs to the MC are expanded to further explore the design space and their effect on the length and connection costs.

Figure 4 shows that connection costs tend to increase when the length increases. A higher density of points exists for the Length between values 8 and 10 m and connection costs between 28 and 32 m. There is not a dominating solution and many outliers as well. The length values range from 7 to 12 m depending on the input combination, which can generate considerable additional conversion costs.

The histogram of the four distributions in Figure 5 also confirms the spread of objective values in a wide range. The length values

Table 9. Probability density functions for case study distributions.

Distribution	Probability density function (PDF)	Parameters
Weibull	$F(x;k,\lambda) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^k}$	$\lambda = 0.5,\ k = 1$
Uniform	$F(x;a,b) = \frac{1}{b-a}$	$b = \max(x)$, $a = \min(x)$
Normal	$F(x;\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$	$\mu = \frac{a+b}{2}$, $\sigma = \frac{(b-a)}{6}$
Beta	$F(x;\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{\alpha-1}(1-x)^{\beta-1}$	$\alpha = 1, \beta = 3$

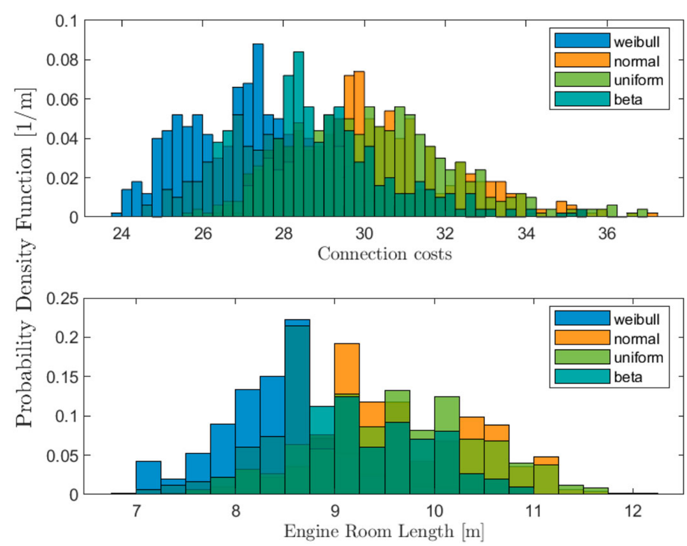

Figure 5. Comparative histogram of engine room length and connection costs.

of approximately 8.6 and 9.2 m present a higher density, but do not dominate the solution space. The input distributions lead to similar connection costs between 26 and 30. There is no clear pattern to the change of the connection costs.

Figure 6 proves that the distribution type affects the mean μ and standard deviation σ of the objectives. Although, all the distribution generated lengths among the interval 8–10 m, the spread of the values is different. In normal and beta distributions, the median (red) line is asymmetric indicating skewness in the distribution. This is confirmed by Table 10. As shown in Figure 6, the connection cost values are also distinguished depending on the distribution and present outliers in every case, indicating an inconsistent response to the input. The distribution choice therefore affects both the length and even more drastically the connection costs.

Table 10 metrics show that the outputs per distribution are clearly separated. The overall sample does not resemble to one distribution and has 0.9 m spread, which is high. Both kurtosis and skewness variation indicate there is not a more frequent length value. Table 11

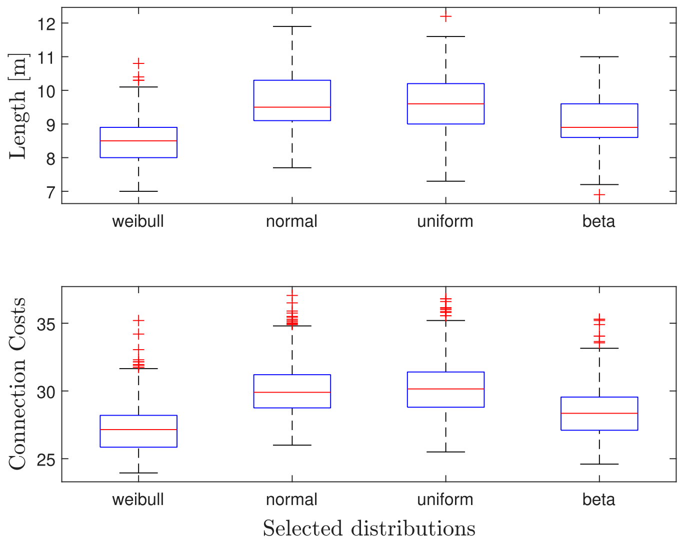

Figure 6. Variation of length and connection costs depending on the selected distributions.

Table 10. Length [m] statistic metrics per distribution and for the overall sample.

Measure	Weibull	Normal	Uniform	Beta	Average
μ	8.49	9.62	9.62	9.04	9.19
σ	0.68	0.81	0.85	0.74	0.90
kurtosis	2.95	2.47	2.66	2.71	2.64
skewness	0.16	0.14	−0.04	0.14	0.17

Table 11. Connection costs statistic metrics per distribution and for the overall sample.

Measure	Weibull	Normal	Uniform	Beta	Average
μ	27.21	30.16	30.24	28.52	29.03
σ	1.77	1.94	2.01	1.89	2.28
kurtosis	4.08	3.24	3.35	1.89	3.09
skewness	0.76	0.63	0.49	0.65	0.40

shows that the value of the overall sample containing all of the distribution scenarios has mean and standard deviation more closely comparable to the uniform distribution. However, the kurtosis for the different distributions is clearly differentiated indicating the different density of values. Therefore one distribution does not fit for all purposes and the distribution should be selected based on the existing knowledge for each PPE system, to demystify the outlined inconsistencies.

To identify arrangement patterns for the BBs that lead to higher probability of specific engine room lengths values, the actual generated layouts were evaluated. The example layout of the simulation shows that the generator-set BB is placed in the aft part of the engine room (see Figure 2) to provide propulsion for the vessel (Poullis 2022; Steiner 2024). This limits the algorithm to arrange the remainder BBs units around it, while there is a fixed width. In a simulation if some of the BBs cannot fit within the width, the engine room is then lengthened. This explains that there are steps in the mean values of lengths depending on the distribution (see Table 6). The difference between the minimum length and the maximum length is more than 5 m, which can lead to considerable conversion costs if the vessel is lengthened (Terün et al. 2022). In the case of an existing vessel, this engine room lengthening can cause loss of cargo space.

4.3. Effect of uncertainty with varied logical architectures and fixed BB dimensions

The findings of Souflis-Rigas et al. (2023) highlighted the need to further investigate and test the way that logical architectures influence the size of the engine room. An MC simulation was performed for the values of the CM. Connection costs weights in the CM become stochastic (see Equation 6), meaning that for example, a connection weight can receive a value of 1, 2 or 3 depending on the sample drawn in MC. The variation in the weights can indicate safety considerations for the dependencies of the PPE systems.

$$CM_{parametric} = \begin{bmatrix} 0 & 2 & 1 & a & b & 1 \\ 2 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 \\ a & 0 & 0 & 0 & 0 & c \\ b & 0 & 1 & 0 & 0 & d \\ 1 & 0 & 1 & c & d & 0 \end{bmatrix} \tag{6}$$

- $a = [1, 3]$ represents uncertainty on the connection between methanol fuel preparation and FC, which means the need for doubled wall piping used for fuel distribution can increase costs.
- $b = [1, 3]$ represents uncertainty on the connection between methanol fuel preparation and Generator-set, as doubled wall piping can increase connection costs.
- $c = [1, 3]$ represents uncertainty on the required electrical cabling between FC and the Switchboard for electrical distribution.
- $d = [1, 3]$ represents uncertainty on the required electrical cabling between the Generator-set and the Switchboard.

For a 500 simulation run, input dimensions are kept fixed and the logical architecture was varied according to Equation (6). The solution space is depicted in Figures 7 and 8. Figure 7 shows that the length of 9 m and 11 m has a high frequency. Connection costs' histogram shape in Figure 7 resembles to that of a normal distribution. This means that the relative positions between BBs and their distances are adjusted per MC iteration. There is a bigger spread in the connection costs values compared to the length, which is logical as different weight factors are applied in the simulation. This case study

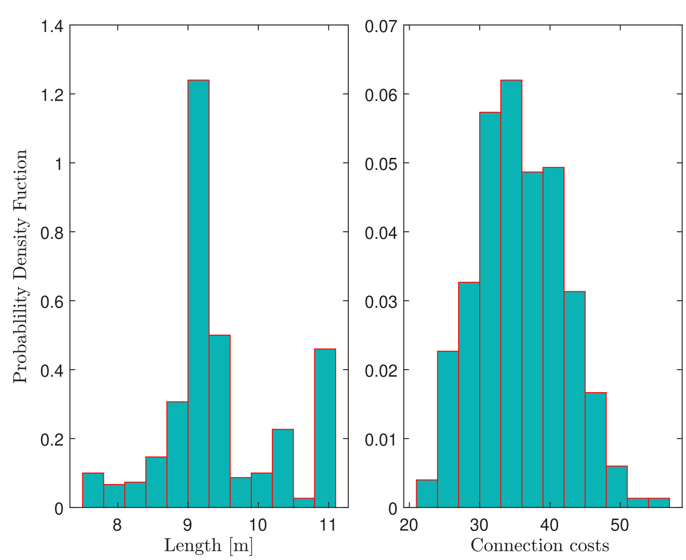

Figure 7. Histogram for the two framework outputs when keeping the dimensions fixed and varying the connection matrix (CM).

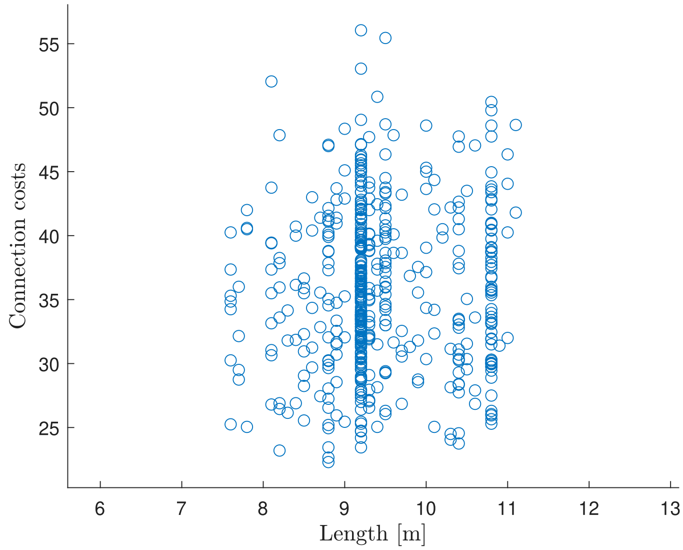

Figure 8. Design space when keeping the dimensions fixed and varying the connection matrix (CM).

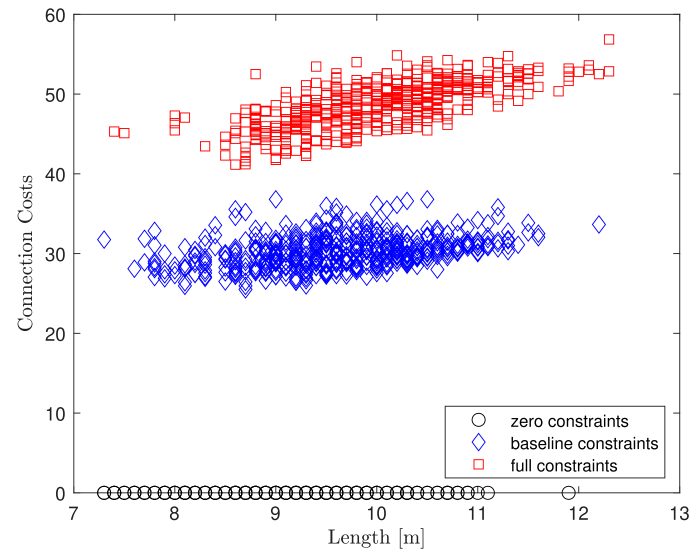

Figure 9. Solution space for the different logical architectures and uncertain dimensions.

served as a sensitivity study, but it is necessary to quantify more accurately the connection costs and link them to possible constraints to be applied based on the BBs dependencies and integration constraints.

Interestingly, a clustering of the engine room length around the values of 9.2 m and 10.8 m is found (see Figure 8). There are less outlier points, which is reasonable because of the fixed BBs dimensions. This highlights the effect of connection costs on the layout arrangement of BBs in the engine room. In spite of the fixed dimensions, a distribution of solutions is generated. The position of the Generator-set affects the solution space that the layout generator can produce. Additionally, the variation of connection weights can reflect the considerations to prioritize components being close or apart to fulfil safety requirements.

4.4. Effect of uncertain BB dimensions and varied logical architectures

This case study aims to explore the influence of uncertainty within the logical architectures by applying two additional connection matrices, namely:

(1) *Zero constraints:* CM with 0 values is implemented, meaning that layouts are generated with length as the only objective.
(2) *Full constraints:* Increased weights are assigned between the BBs that potentially limit the layout options and are implemented in Equation (7).

$$\mathrm{CM}_{\textit{full constraints}} = \begin{bmatrix} 0 & 2 & 1 & 3 & 3 & 1 \\ 2 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 \\ 3 & 0 & 0 & 0 & 0 & 1 \\ 3 & 0 & 1 & 0 & 0 & 4 \\ 1 & 0 & 1 & 1 & 4 & 0 \end{bmatrix} \tag{7}$$

Figure 9 shows the data clustered depending on the logical architecture scenario. It is natural that the *zero constraints* scenario generates a flat line and is therefore not included in the comparison of connection costs. The full constraints scenario generates a considerable increase in connection costs and also a shift of points towards the right meaning a higher overall length. This pattern is similarly observed in Figure 10, in which many points are outliers. The existence of outliers is confirmed by the kurtosis values in Tables 12 and 13. This points to an inconsistent and complex impact of the logical architecture and BBs size uncertainties in spite of the simplified case study.

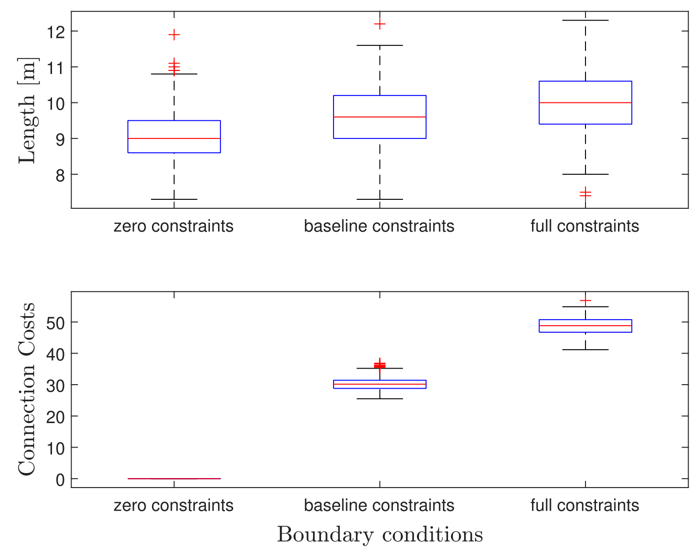

Figure 10. Variation of length and connection costs depending on the allocated connection matrices.

Table 12. Length [m] statistics per logical architecture scenario.

Measure	Zero	Baseline	Full constraints
μ	9.07	9.62	10.02
σ	0.77	0.85	0.82
kurtosis	3.05	2.66	2.95
skewness	0.16	−0.04	0.06

Similarly, Figures 10 and 11 show how the length distribution varies between the different experiments. *Full* and *zero constraint* scenarios appear to have different behaviours despite the minor modifications per logical architecture scenario. Both of them lead

Table 13. Connection costs statistics per scenario.

Measure	Baseline	Full constraints
μ	30.24	48.69
σ	2.01	2.78
kurtosis	3.35	2.60
skewness	0.49	−0.24

to a different engine room length range compared to the baseline scenario.

Figure 11 shows that the distribution shapes of length differ, while connection costs resemble more to a normal distribution. The statistics of length and connection costs provided in Tables 12 and 13 show the variation of the possible outcomes depending on the connection matrices defined, as well as the skew of the distributions. As a result, there is no consistent distribution to describe the outcomes of the experiment, meaning that the change in logical architecture and dimensions of PPE systems, cannot be uniformly described. Understanding the trade off between connection costs and lengthening conversion of the vessel can lead to risk mitigation for the designs.

5. Discussion, conclusion and future research

5.1. Discussion

The integration of methanol fuelled PPEs leads to overlooked uncertainties regarding their actual size, shape and the requirements for their integration. Previous studies have failed to account for these uncertainties, resulting in designs with limitations in range, speed, and in some cases, ambiguous size increases.

An uncertainty evaluation framework was developed to account for the identified uncertainties. Integrating a multi-objective optimization process in Monte Carlo simulations increases computational modelling cost and complexity.

Building upon the previous study (Souflis-Rigas et al. 2023), the uncertainty factors of sizing and logical architecture of systems are investigated in three separate cases to better examine the inconsistency between the input dimensions and the outputs of the problem. The implementation of different distributions indicated that careful selection of input distribution is necessary. Clustering of solutions around specific length values indicates that lengthening occurred when PPEs do not fit width wise. Logical architecture variation with fixed dimensions led to a design space with multiple outputs and discrete lengths, which emphasizes the importance of defining connection costs weights and thus systems dependencies well.

The layout integration *does not* aims to find the optimal configuration of the engine room, but instead to establish insights into the variation of the generated designs under uncertain conditions. Figure 10 indicates that *zero constraints* or *full constraints* cause change in the length distribution in spite of the same uniform distribution. Relationship between input and output distribution is nonlinear. The case study for this framework was mostly limited to the physical and logical architecture layers.

Although this study accounted for only 10% of the uncertainties in component sizing, the generated solution space exhibited a 5-m range between the minimum and maximum length values. This indicates large ambiguity for the conversion costs, which the proposed framework highlighted.

5.2. Conclusion

The presented study established the uncertainties relating to power propulsion energy (PPE) systems rooting mainly on technical and regulatory factors. The review of the state-of-the-art in methanol fuelled vessels, systems and design methods showed that many elements are overlooked when integrating the PPE systems on notional or existing ships that cause compromises in operational characteristics or ambiguous size increase. The uncertainties that are presented

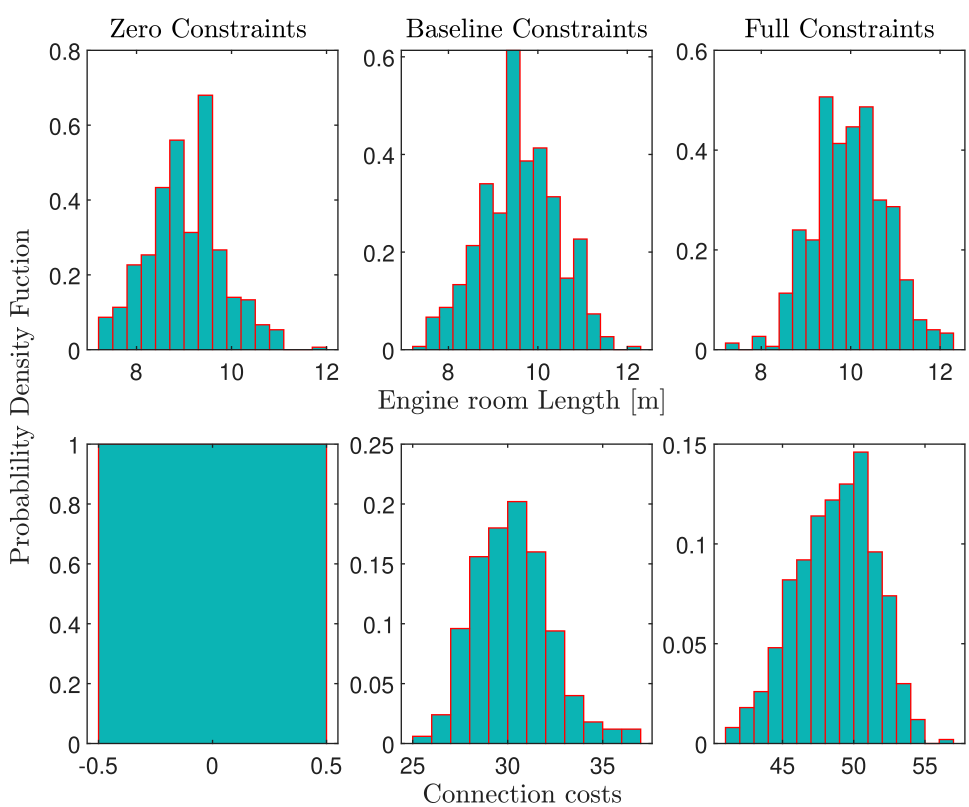

Figure 11. Length and connection cost distribution for uncertain dimensions and variable connection costs.

in Tables 1 and 6 can prove critical design drivers. Based on these, an uncertainty evaluation framework is proposed (see Figure 1), which centres around the inclusion of uncertainty linked to the PPE systems logical and physical architecture.

For the framework application, a case study for a notional methanol yacht engine room was set up to evaluate the uncertainties within the physical space combined with varied logical architectures. The outcome confirms the inconsistency of output size reported in the literature. The distribution shapes of the output variable differ from all the implemented input distributions, meaning that the size alteration does not always prove to be fully influential, but critical thresholds lead to discrete steps in length increase. Variation in logical architectures results in distinct distribution patterns even with fixed input dimensions, leading to outcomes that cannot be described in a unified way. Further exploring techniques for logical architecture modelling such as network theory sets an interesting research direction.

5.3. Future research

Future modelling efforts will focus on applying improved network theory metrics to better understand dependencies among systems and locating systems that prove influential to design change. The aim is to trace the connection between logical and physical architecture. Additionally, advancements in the mathematical formulation for the layout optimization can facilitate scaled up case studies. As the methanol PPE systems are under development and vessels need to sail for a 20–30 year lifespan, integrating this tool with a lifecycle analysis framework is part of the future research (Souflis-Rigas et al. 2024).

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Supplementary material

The data underlying the case studies of the methodology presented in the paper can be found in the following repository: https://doi.org/10.4121/f5f313c2-c5a3-40c2-a5ea-f7f64d92de51.

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