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Establishing the Influence of Methanol Fuelled Power Propulsion and Energy Systems on Ship Design

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Abstract

The adoption of alternative energy carriers is one of the key ways to meet the increasingly stricter emission regulations faced by shipping vessels from the international maritime organisation (IMO) and European Commission. To support this objective, this study examines the challenges and uncertainties associated with implementing a methanol power propulsion and energy (PPE) system on the design of a vessel. This paper argues that new fuels, such as methanol, should be treated as disruptive innovations due, in part, to the uncertainties surrounding their implementation. Their integration causes challenges regarding systems selection, layout design, and maintaining strict safety measures. In the case of methanol, current research treats the fuel as a system conversion based on diesel fuel. This paper provides a review of the state-of-the-art on the design of methanol fuelled vessels, and identifies a research gap related to the need for a new suitable design method for the design of ships integrating future alternatively fuelled PPE systems. A design approach inspired by model-based systems engineering integrating uncertainty modelling is proposed to examine the influence of uncertainty on the design of the vessels. The impact of uncertainty on the design is investigated through a case study of a simplified engine room layout utilizing a genetic algorithm to produce layouts for variable PPE systems dimensions within a Monte Carlo simulation.

Keywords: Methanol; Ship design; Uncertainty propagation; Systems Integration; Alternative power propulsion and energy systems.

1 INTRODUCTION

The energy transition and the effort towards the decarbonization of the shipping industry is an important step towards addressing climate change as the maritime industry accounts for approximately 3% of greenhouse gas (GHG) emissions [1]. The International Maritime Organization (IMO) has set a target of net zero GHG emissions in 2050 compared to 2008 [2]. Accordingly, the European Commission is introducing a set of policy actions that target a climate neutral Europe in 2050 [3] and the European Parliament council has announced the target of mitigating GHG intensity by 80% by 2050 [4].

To address this, the IMO has introduced various performance indicators that assess a vessel's CO_2 emissions, including the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Index (CII) [5] (MEPC 76). In addition, vessels also need to conform to regulations for SO_X [6] and NO_X [7] which may require the adoption of further technology. Technological innovation is thus required to meet these upcoming regulations and climate goals.

One of the key ways to meet this demand is by adopting alternative fuels [1]. Several studies have compared alternative fuel options from a lifecycle perspective both economically and environmentally, such as [8]–[10]. Transitioning to alternative fuels is not without trouble, as Lindstad [11] demonstrated that adopting 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 increase by a factor of 2.3 for methanol and 7.1 for liquid hydrogen[12].This inevitably leads to an increased demand for voluminous storage areas and challenges in their integration into the vessel. Various studies comparing alternative fuels integration have generated different outcomes regarding space requirements owing to various assumptions about future fuels. New challenges arise from alternative fuel integration due to storage and handling, vessel performance, space allocation, safety equipment, and safe handling of the fuel [12]. In combination with the existing complexity of conceptual ship design [13], the need arises to understand the influence of the novel power propulsion and energy (PPE) sys-

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tems on the design of the vessels as early as possible in the design process.

This paper focuses specifically on methanol as a fuel, since it eliminates almost all SO_X, drastically reduces NO_X in comparison to conventional marine diesel [14], and can be produced in clean ways from biomass or water electrolysis. This means that it can potentially turn into an almost carbon neutral fuel [15], [16]. The environmentally clean versions of methanol, biomethanol and e-methanol, prove highly cost competitive in comparison to other alternative fuels [10].

The PPE systems required for methanol differ from traditional fuels and may even require the adoption of additional technologies throughout the ship lifecycle. Section 2 reviews the challenges of methanol PPE systems integration. This review is complemented by a case study in Section 4 that investigates the influence of the uncertainty in the size, dimensions, and logical connections of PPE components and layout arrangements on a simplified engine room.

2 PROBLEM FORMULATION

To formulate the problem of the influence of future methanol PPEs on the design of ships, it is helpful to first define the main categories of the systems and to identify their associated challenges. The categories are split based on the work of [17]:

- 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, as described in Section 2.1.
- The *auxiliary power generation systems* describe the systems used to generate electric power and auxiliary loads such as pumps and generators, discussed in Section 2.2.
- 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, discussed in Section 2.2.

Additionally, the State of the Art of the design approaches attempting to integrate methanol PPEs is looked into and based on the identified research gaps, a suitable design framework is proposed.

2.1 Storage challenges due to methanol fuel properties

It is important to understand the properties of the fuel, to comprehend the integration of methanol energy storage systems. 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) [18], [19]. This code has been developed for gas or low flashpoint fuels and leads to the requirement of cofferdams around the tanks, except for the areas that are adjacent to the shell plating below the minimum waterline [20]. This leads to a considerable space demand that must be handled within the hull.

IMO [21] has established guidelines especially for methyl alcohol fuels that are under constant review based on the knowledge gained through operation [22]. In terms of storage and handling, methanol shares more common traits with diesel fuel than LNG (see Table 1) meaning that it can be stored in conventional tanks [8], [23].

Table 1: Comparative chemical properties of diesel oil, methanol, and LNG (adopted from [15]).
LHV: Lower Heating Value

Properties	Diesel Oil	Methanol	LNG
LHV (MJ /kg)	42.6	19.9	$48-50$
Boiling point ($°C$)	$180-360$	65	-161.4
Flash point ($°C$)	78	11	-136

The tank volume storage becomes critical in the case of methanol, because it has approximately half the energy density of conventional diesel, as illustrated in Table 1. Kries [24] showed that a 50% increase in the usable tank volume can be achieved by adopting a smaller cofferdam. Furthermore, Ban and Bebić [12] implemented a hazard identification study (HAZID) to be able to store methanol fuel in ballast tanks in a retrofit case and found that small adjustments on sailing range or speed are required. Additionally, [25] argued that for a diesel fuel capacity of 600 m^3, an equivalent 1300 - 1500 m^3 methanol fuel capacity is necessary. These findings indicate a level of uncertainty in the additional storage space requirement.

Safety concerns arise from the use of methanol as an energy carrier because of its toxic and flammable properties [26] (its flames are invisible during daylight [18] and form no smoke [27]), which leads to additional safety equipment requirements [26]. Thus, methanol cannot be placed adjacent to any manned or freely accessible space of the vessel for fire safety. This poses limitations to the layout of the systems within the vessel. Methanol also presents a corrosive behaviour that increases when metallic materials such as aluminium and titanium alloys exist in the same environment. Thus, stainless steel and appropriate protective coating (such as zinc) are among the solutions applied to the tank interior [18]. This raises a concern regarding the cost and the maintenance demands for the vessels and means that careful materials selection is necessary.

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

This section provides a review of the various technologies that are already available or under development to facilitate the shift towards methanol as an energy carrier. Methanol can be burned in an engine, a high temperature fuel cell or be used as a hydrogen carrier in fuel cells. Each propulsion option has relative advantages. Table 2 presents that engines offer a known technology, easy to adapt, with a long lifetime [28], but also with higher emissions, especially NO_X, and lower efficiencies, when compared to fuel cells. This has lead to the consideration of hybrid systems, next to the individual systems, so no propulsion choice is currently absolute.

Methanol combustion in internal combustion engines (ICE), drastically reduces SO_X and particulate matter (PM) emissions [16], [27], [29]. When green or e-methanol is adopted [11] they provide a profound reduction in CO_2 emissions on a Well-to-Wake (WTW) scope. Methanol generated from natural gas barely reduces [28] or even slightly increases CO_2 emissions on a WTW level [11], [30]. Even worse on a WTW level, approximately 6 kWhs of e-methanol are required to generate 1 kWh on the propeller [31]. Looking into the details of the engine many more variations can be observed. Methanol does not burn by itself, it requires a pilot fuel to achieve this [16]. As a result, variations can be found in the location in the process where methanol is mixed with the pilot fuel, but also the choice of pilot fuel and engine type (e.g. compression vs spark) vary in the chosen solutions. The two main combustion concepts are the spark ignited (SI) engine and the compression ignited engine (CI) engine. The SI engine operates only on methanol and has been proven to comply with tier III NO_X emissions levels [16]. On the other hand, the CI engine can offer fuel flexibility and has been more widely used on projects to date. However, CI engines only comply with tier II NO_X emission levels [27], thus requiring an after-treatment such as a selective catalyst reduction (SCR) unit, water fuel mix technique, or an exhaust gas recirculation system (EGR) [16]. SCR and EGR systems take up additional internal volume in comparison to the fuel - water blending technique. Recent studies show that methanol engines operate at the same efficiency (η) as diesel engines or even higher [27], at approximately 40% [8].

In combination with the fact that a dual fuel strategy requires tanks for both methanol and diesel, the size and shape of the PPEs becomes even more unclear, causing uncertainty in the actual layout arrangement of the PPEs. In addition, waste heat recovery (WHR) systems may be part of the PPE to use the waste energy of exhaust gases and produce further mechanical energy. However, these WHR systems are voluminous [16]. On the one hand, improvements in efficiency are expected for methanol fuel cells, but on the other hand, the configurations of large-scale systems (including cooling, control, etc.) are still under development, making the size of the system debatable. Technology readiness level (TRL) [32] is low and they have not been yet commercially applied [8]. In combination with their shorter lifecycle [24], they become a less attractive option to consider. Therefore, they were not further investigated within the scope of this study.

Table 2: Overview of main methanol propulsion options [8], [16]

Properties	ICE	Fuel Cells
Advantages	High TRL Reliability Easy conversion	Efficiency (η) (60%) Lower emissions
Disadvantages	Efficiency (η) (40%) More emissions	Low TRL Lifecycle (8 - 10) Years

Recent studies on the effect of alternatively fuelled PPE configurations on the size of navy vessels have provided inconsistent findings (see Table 3), not only within a single study but also between studies. One of the primary assumptions in the studies [33], [34] is that the additional weight by the integration of methanol fuelled systems does not lead to an increase in power demand. Snaathorst [35] investigated the effect of alternative fuels integration by using a parametric tool based on empirical equations and ship data, computed the impact on the size and consequently the resistance of the vessel that leads to increased power demand. He found that the increase in size can vary from 2,4 - 6%

which leads to an additional powering demand of 2,7% on average.

Table 3: Effect of displacement of methanol fuelled PPE systems on navy vessels

Propulsion Configuration	Estimated Δ increase [%]	Design Tool	Reference
Hybrid, ICE FC, Gas	18 - 25 %	Parametric tool	[33]
Hybrid, ICE Gas	1,4 - 20 %	Layout modelling	[34]
Hybrid, ICE FC, Gas	8 - 15 %	Parametric tool	[36]

Lastly, a unanimous trend in conversions and retrofits to methanol is to first lengthen the vessel to generate additional space [24], [34], [35]. This is rational as increasing the length can have a limited effect on the resistance [37]. However in most retrofit cases, they maintain the existing hull shape and explore alternative placement options for the additional methanol tanks [15], [30], [34]. This paper argues that:

- There is a large variety of systems under development that need to be integrated into the vessel.
- The exact shapes and quantities of these components are unknown. This study refers to the components as the *building blocks* (BB) of the PPEs.
- Different propulsion choices lead to different PPE shapes that are not yet fully defined. Thus, the overall impact on ship design is not yet fully deterministic.

2.3 State-of-the-Art of the design approaches of methanol fuelled ships

Maersk is currently investing in methanol fuelled vessels [38], underlining the interest for alternative fuels adoption in the maritime sector. 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 4 vessels with different missions and sailing speeds, but similar sizes, require highly different installed power. Zuidgeest [30] showed that a 30% increase in speed can lead to an 80% increase in fuel consumption, as also logically follows from the speed power relationship [39]. Considering that slow steaming [40] and engine derating [16] have proven to be effective measures for emission mitigation, there is a decrease in the installed power demand [41]. This has a large effect on the size of the machinery equipment and the overall size of the ship. Therefore the size of the ship depends, in part, on the operational requirements set for it.

The requirements regarding sailing speed and range may still be under discussion and thus uncertain during the design phase while they simultaneously have a large influence on the systems layout of the vessel. Therefore the relationship between the operational, functional, and physical requirements of methanol PPE systems must be captured within the design process.

To date, research projects have primarily focused on conversion and retrofits of diesel fuelled vessels. The retrofit as a process leads to having a vessel with a given hull shape and inner system layout arrangement. This indicates an already set design space for the systems, that rather limits the alternatives for reconfiguration as shown below. 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 [23], [29] that applied a new high pressure common rail system, high pressure pumps, and the corresponding safety equipment. Consequently the integration of so many systems leads to large connection costs between the systems, meaning new control systems and cable lengths [29] and if their layout logic is wrong, can lead to unwanted connection costs. Thus, the manner in which the systems are placed and the proximity between relevant systems has an influence on the size of the ESS and the engine room.

Zuidgeest [30] explored the general arrangement of an existing vessel and potential propulsion alternatives.Pothaar [34] used a 3D modelling tool to evaluate the effect of methanol integration in reference to an existing ship. Ban [12] performed a HAZID risk design approach to integrate the additional methanol tanks into the ballast tanks location with minimized effect. The Green Maritime Methanol project [43] investigated a variety of vessels such as those listed in Table 4, 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 to the design spiral approach and only explore an existing design space to place the methanol tanks, meaning that the design choices are rather limited. There is the need to design and explore the design space without strict initial conditions that limit the possible solutions.

Table 4: Comparison of principal characteristics of methanol fuelled vessels

Vessel Type	Vessel size [t]	Sailing Speed [kn]	Installed Power [kW]	Reference
TSHD	DWT 4200	11	4600	[12]
Stena Germanica ferry	GT 52000	22	24000	[29], [42]
General Cargo Vessel	DWT 7000	9.5	1600	[30]
Navy Vessel	Δ 7200	18	50000	[34]
Cable laying vessel	DWT 8400	12.4	11000	[43]

The use cases of green maritime methanol (GMM) [43] have demonstrated that a retrofit can prove more complex and expensive. In case of limited space, the conversion can become more complex and unfeasible as was the case for an inland patrol vessel. The conversions were categorized as either major or minor. Major conversions demanded an enlargement with several frames for the installation of the methanol system, while minor conversions included adjustments in the general arrangement of the vessel. The case of a small port patrol vessel proved unsuitable for conversion. Furthermore, the operation on a dual fuel strategy using both methanol and diesel can lead to a mitigated decrease in the range [43] in excess of 20%.

For different vessel types, the sailing range was reduced approximately 40% - 50%, when integrating methanol [30], [34], [43]. In contrast, Ban [12] found that the range for a two-week mission remains almost identical. Consequently treating the methanol integration just as a modification in an existing design rationale leads to bottlenecks and unexpected compromises in the design and operation of the vessel.

2.4 Requirements for Design Framework

The proposed Design Framework is necessary to integrate the uncertainty, as inconsistencies have been found regarding the size of the PPE subsystems and their effect on the overall ship design, as presented in sections 2.1, 2.2, 2.3. As categorized [44], uncertainties can be divided into two main categories:

- *Epistemic*: is generated by insufficient knowledge regarding a problem or technology and is mitigated by gaining more information and understanding via simulations, experiments etc..
- *Aleatory*: is caused by the randomness of outcomes in the nature and cannot be mitigated via modelling.

The uncertainty type addressed in this problem is epistemic. Further knowledge regarding technology development can lead to mitigation of the uncertainty regarding the sizing and dimensioning of the building blocks (BB) - size of the subsystems. Consequently, modelling the uncertainty of the parameters related to these systems is a prominent requirement.

To establish the design method required for this research, it is essential to clarify both the main research gaps identified above and the matching method requirements, which are presented in Table 5. Because many PPE systems are still under development, the level of complexity increases.

As stated in the [45] there is the need to handle the ship as part of a larger system towards more environmentally sustainable vessels. The design should thus be interconnected with the requirements of the stakeholders, such as: regulatory authorities, shipowners, shipyards, or class societies. There is also a need to investigate various scenarios regarding technical, economic, environmental and safety performance from a lifecycle perspective [45].

Relevant studies have been evaluated to shape the proposed method (see Table 6). Therefore, it is clear that different aspects of each methodology need to be combined to meet all the requirements. The design approach that shows the most promise and satisfies most requirements is model based systems engineering (MBSE), as it provides the traceability of changes and interaction between the various requirements in design highlighted in Table 7 [46], [47]. In Table 6, the MBSE approach is only found at a basic level on the work of Rehn [13] and on the application of the Ship Power and Energy Concept (SPEC) tool developed by MARIN to a hydrogen fuelled vessel [46]. The approach is based on the analysis of the design process into 4 main layers inspired by systems engineering (SE) [48]

- *Operational Analysis*, from which the basic requirements for the operation of the vessel are established
- *Functional Requirements* which defines the functions expected to be fulfilled by the system

Table 5: Research Method Requirements

Research Gap	Method Requirement
Uncertainty on influence of PPE on ship design	Traceability of changes Uncertainty modelling
Accurate size effect consideration	Layout integration
Uncertainty on operational requirements	Interaction between operational requirements and physical space
Variation of new environmental regulations requirements	Lifecycle assessment

- *Logical Architecture*, which defines in further detail the system technologies that are to be used to fulfil the above requirements and their possible interconnections to comply with different regulations requirements [46].
- *Physical Architecture* defines the actual placement of the systems in the physical space (e.g. with a general arrangement plan).

The uncertainties outlined above are categorized within these layers, as listed in Table 7. As a first step in this research, this paper focuses on the integration of uncertainty within the physical layer, while considering variations in the logical architecture and their effect on the overall shape of the engine room design.

Table 7: Uncertainties found per MBSE Layer

MBSE Layer	Uncertainty
Requirements	Range, speed
Functional	Safety measures required
Logical	Placement and connection patterns systems due to safety
Physical	Actual size and amount of required PPE systems

3 PROPOSED DESIGN FRAMEWORK

Based on the findings in Tables 6 and 7, there is the need to integrate uncertainty into the layout design process of machinery spaces owing, in part, to uncertainty in the size and amount of integrated systems. This can also be due to the uncertainty in the original design requirements regarding ship speed and range parameters, which influence the installed power and sizing of the main propulsion equipment. Dimensions uncertainty can root also from the functional requirement for safety as relevant regulations and technology are still under development. Additionally the safety requirements owing to the properties of methanol pose limitations on spaces not being adjacent to each other due to fire risks. For this reason the logical architecture is taken into account within the layout modelling at a high level in this research, posing layout boundary conditions for the integrated components. Requirements from different levels trace back to uncertainty in the physical space.

The proposed modelling process is illustrated in Figure 1. The emphasis is on the physical architecture layer of the MBSE coupled with variations in logical architecture. The layout generation algorithm (based on [51]) has been integrated into a Monte Carlo simulation (MCS) to capture the already discussed uncertainty aspects. Poullis [51] set up a layout algorithm for the engine room of a hybrid methanol fuelled yacht. This study extended this model to turn the layout algorithm into a stochastic model to generate the distributions of the output variables.

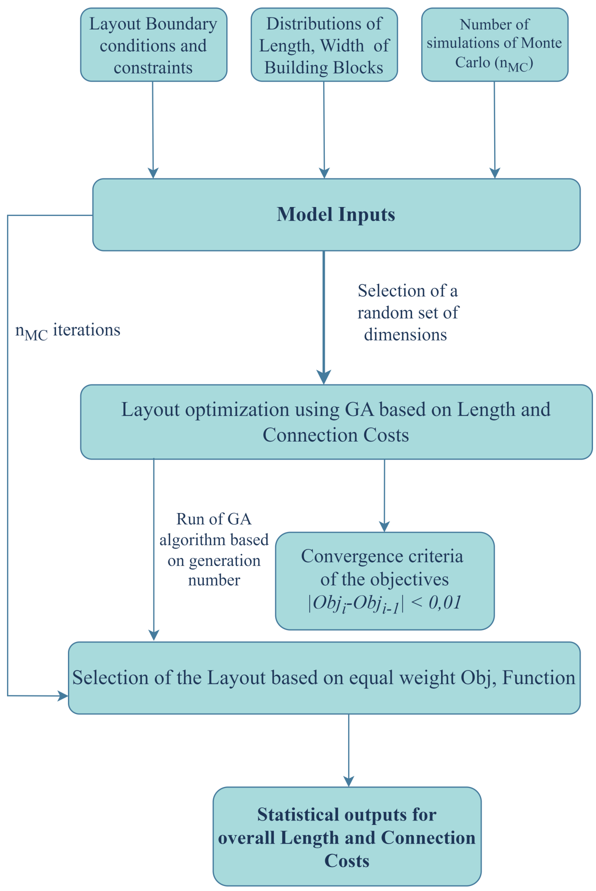

Figure 1: Proposed design model process

Table 6: Relevant literature for method requirements

Traceability of changes	**Uncertainty modelling**	**Layout integration**	**Requirements and physical design interaction**	**Lifecycle evaluation**	**Approach name**
X	X	✓	✓	✓	Design Parametric tool [24]
X	X	X	✓	X	Design spiral for retrofit [43]
X	X	✓	X	✓	Lifecycle choices analysis [49]
✓	✓	X	X	✓	SE design under uncertainty [13]
✓	X	X	X	✓	MBSE application [46]
X	X	✓	X	✓	Stochastic parametric tool [50]
X	X	✓	X	X	Machinery layout tool [51], [52]

The MCS is applied to understand the impact of variable dimensions to the simplified engine room of a vessel, which potentially affects the size of the vessel. MCS has previously been applied by Kana [53] to establish an understanding of the way that different emission regulations scenarios influence the conversion decision for an LNG powered containership. Coraddu [54] integrated a MCS to approximate the EEOI while having two stochastic inputs Δ (displacement) and v_s (sailing speed). Dall'armi [55] followed this approach to apply a MCS analysis to investigate influence of the fuel cells costs to the optimal operation of a hydrogen ferry. Curto [56] applied MCS to determine the influence of various uncertainty types on the behaviour of project costs. Thus MCS is a promising method for exploring this type of problem, whilst being simple to implement.

Using this model, 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 of a simplified engine room. A uniform distribution has been selected for the input variables (length and width of BBs), as it appoints equally likely outcomes to all the variables within the defined interval.

3.1 Layout Algorithm within Monte Carlo simulation

The layout modelling approach selected is based on solving the facility layout problem (FLP), used by [51] to model the shipboard layout of a machinery space. As defined in [57], the FLP can be described as the arrangement of units (BBs in this case) in a plant area to attain the most effective layout in accordance with predefined objectives and constraints. In the model proposed by Poullis[51], 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 proposed model generates layouts for a simplified engine room with fixed width. Integer constraints are introduced to tune the rotational ability of the BBs, by using a value of 1 for rotational ability and 0 for non-rotation. A coordinate-based system is used for the layout generation. The BBs are modelled as boxes as depicted in Figure 3. They have an input and output point that coincide with the start and the end of the box respectively, as defined in [51]. The minimum length is computed by finding the right most BB coordinate.

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 euclidean distances between the various systems and multiplying with the corresponding cost factor (Equation 1) [52]. The cost of each connection is allocated using a connection matrix (CM) that includes weighting factors for connecting either to the input or the output of the BB.

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

The multi-objective optimisation is implemented using Deb's NSGA-II [58] incorporated into the MATLAB global optimisation toolbox [59]. The critical parameters to define the optimization process are listed in Table 8. The population size is set to 400 by trial and error. Each BB has a set of three decision variables: length, width and rotational freedom. Five BBs are selected for this case study. Therefore, there are 15 decision variables ($n_{variables}$) in this case study.

Table 8: 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

A convergence criterion has been applied to compare the outcome of the objective functions based on Equation 2:

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

The convergence criterion (Equation 2), regarding the values of the objectives: length, connection costs is applied to reduce computational time when the GA cannot provide fundamental layout improvements. GA produces more than one solutions per set of inputs. The maximum value of the objectives out of these solutions per MC run has been used to normalize the values of the objectives in Equation 3 and thus receive values in the range of 0 to 1. Each set of inputs needs to match one layout output to generate a distribution of engine room length and connection costs outputs within the MC simulation. This technique allows to observe the influence of variable dimensions on the overall size of the engine room. Therefore, the selection equation in Equation 3 is applied, which allocates equal weight factors to the objectives of the problem:

$$minObj = min(\sum_{i=1}^{2} w_i \cdot \frac{Obj_i}{maxObj_i}), w_i = 0.5 \qquad (3)$$

The GA output that minimizes the value of Equation 3 is integrated into the MC simulation output. Equal weight factors have been assigned to the Objectives of the problem and the objectives are normalized by dividing with the maximum value of each objective respectively per GA run. The objectives compared in the minimization Equation 3 receive values in the range of 0 to 1, which makes the length and connection costs values equally important.

The solution minimizing Equation 3 is selected and is part of the output statistical data of the MC simulation, regarding length and connection cost. For the case study two main concepts are examined:

1. Impact of variable BB dimensions on the length and connection costs of the engine room with a standard logical architecture
2. Impact of alternative logical architectures on the length and connection costs of the engine room

4 CASE STUDY

The proposed model is used to generate multiple layouts of a simplified engine room with main components. Five BBs that constitute an engine room were selected, as defined in [39], [51], with their variable dimensions (between 15-20 %) provided in Table 9:

- Main Engine
- Fuel Cells
- Fuel Handling room
- Generators
- Control Switchboard room

Table 9: Case Study Dimensions

Building Block	**Width [m]**	**Length [m]**
Methanol Fuel Preparation[1]	1.6 - 2.1	2.6 - 3.5
Fuel Cell [2]	0.6 - 0.9	1.1 - 1.4
Main Engine [3]	1.2 - 1.5	1.4 - 1.9
ESM Machine [4]	0.6 - 0.9	1.1 - 1.4
DC Distribution [5]	0.8 - 1.1	3.8 - 5.1

$$CM_{baseline} = \begin{bmatrix} 0 & 0 & 2 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 5 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 2 & 0 & 0 & 0 \end{bmatrix} \qquad (4)$$

The connection matrix, CM_{normal}, expresses the importance of the connection between the different components, with 0 meaning a connection of minimum importance and 5 a highly important connection and thus components should be in close proximity. The definition of the specific connections was elaborated on in [51]. The matrix in Equation 4 introduces to the layout algorithm, whether BBs should be adjacent or apart, based on the connection costs. To an extent, this reflects the logical architecture that can be implemented. The output variables of the simulation are the Length and the Connection Costs of the simplified engine room, which are also the objectives of the GA algorithm.

4.1 Effect of Uncertainty

Before exploring the results, the convergence of the MCS was determined. Here, 1% was deemed sufficient convergence, and was evaluated based on the cumulative incremental difference (CID) defined in Equation 5. CID expresses the alteration of the mean value (μ) of length and connection cost respectively per MC simulation. As shown in Figure 2 acceptable convergence was achieved within the 400 simulation runs, because the CID values remained within acceptable range of the 1% accuracy. The same accuracy was selected in Equation 2 for the GA convergence, because it is reasonable for both parts of the simulation to have the same level of accuracy. For this set up, the simulation duration was approximately 2 hours per scenario using the Delft Blue supercomputer [60]. A representative layout of the simulation is shown in Figure 3. The presented layout has values similar to the mean values of the length and connection costs in the MC simulation with the baseline logical architecture defined by Equation 4.

$$CID = \frac{\mu_{Objective(i)} - \mu_{Oblective(i-1)}}{N} \quad (5)$$

N:number of runs

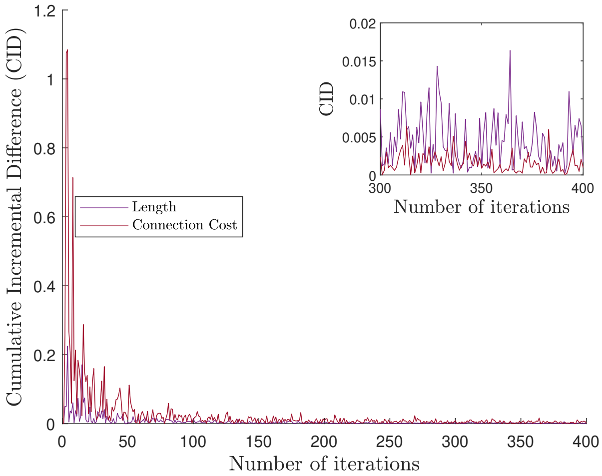

Figure 2: Convergence of the Monte Carlo simulation

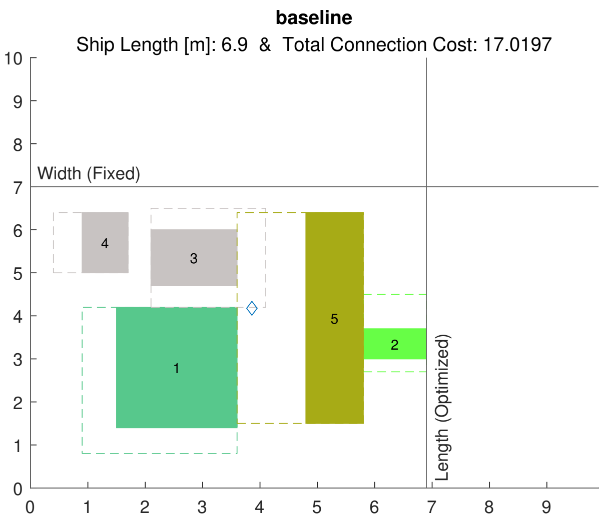

Figure 3: Representative layout generated during simulation with the baseline logical architecture and the mean length

The MC solution space of the 400 runs is presented in Figure 4, where there is no clear correlation between the length and connection costs. Although there is a concentration of points around the mean values of the experiment, simultaneously there are points with an inconsistent behaviour. Figure 5 complements this observation as the distribution especially of the length, does not clearly relate to any of the standard distributions. The solution points are widely spread and exhibit significant variability compared with an evenly spread uniform distribution.

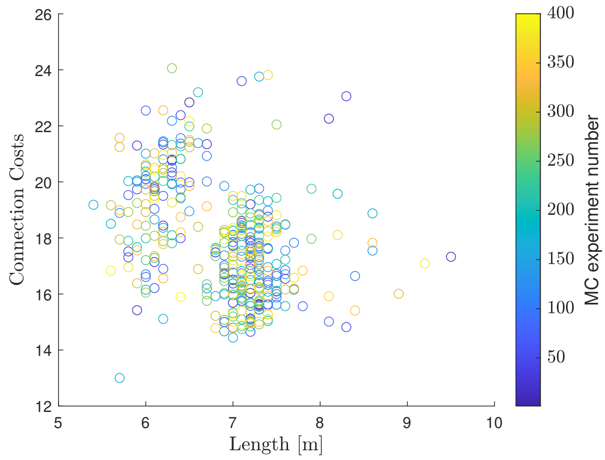

Figure 4: Solution space of the Monte Carlo simulation

Figure 5 presents the histograms of the length and connection costs, where the distributions of the outputs show a clear non-uniform behaviour contrary to the inputs. This underscores the complex relationship uncertainty plays in the integration of methanol fuelled systems and its influence on the design space. When considering the variety of PPE systems to be included in a full-scale ship design, the complexity of the design process increases.

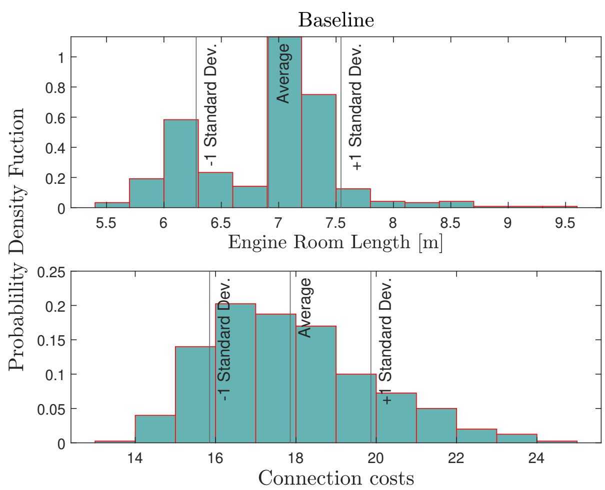

Figure 5: Histogram of engine room length and connection costs

4.2 Effect of uncertainty with varied logical architectures

The aim of this experiment is to explore the influence of uncertainty within the logical architectures by applying two additional connection matrices, namely:

1. *Zero constraints*, meaning that a zero constraint matrix is implemented, and
2. *Full constraints*, which has minor adjustments compared to the baseline CM in Section 4.1. Changes were made to allocate higher CCs between the BBs that potentially limit the layout options and are implemented in Equation 6.

$$CM_{fullconstraints} = \begin{bmatrix} 0 & 0 & 2 & 0 & 0 \\ 2 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 5 & 0 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 2 & 0 & 1 & 0 \end{bmatrix} \quad (6)$$

Similar to the baseline case, the solution space is generated to compare the behaviour of the different logical architecture scenarios. Figure 6 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 below. The full constraints scenario generates a considerable increase in connection costs, but also a shift of points towards the left meaning a lower overall length. This pattern is similarly observed in Figure 7, in which many points are outliers, meaning that they fall outside the consistent box plot pattern. The existence of outliers is confirmed by the kurtosis values in Tables 10 and 11. This points to an inconsistent and complex impact of the logical architecture and BBs size uncertainties even in a very simplified case study, which cannot be logically explained and requires further research.

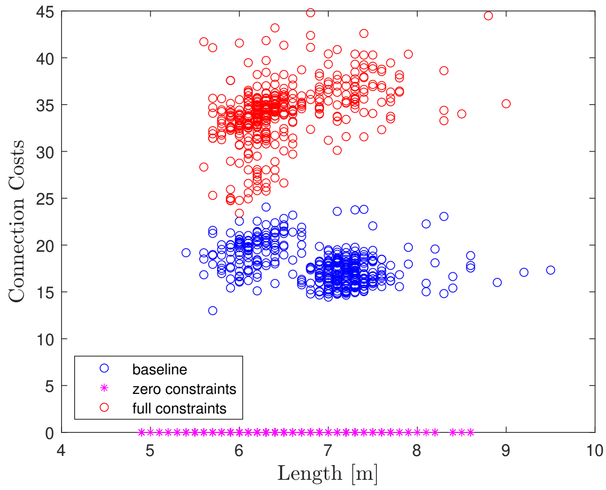

Figure 6: Solution Space for different logical architectures

Similarly, Figures 7 and 8 show how the length distribution varies between the different experiments. *Full* and *zero constraints* scenarios appear to have different behaviours despite the minor modifications per logical architecture scenario. Both of them lead to a reduced engine room length compared to the baseline scenario.

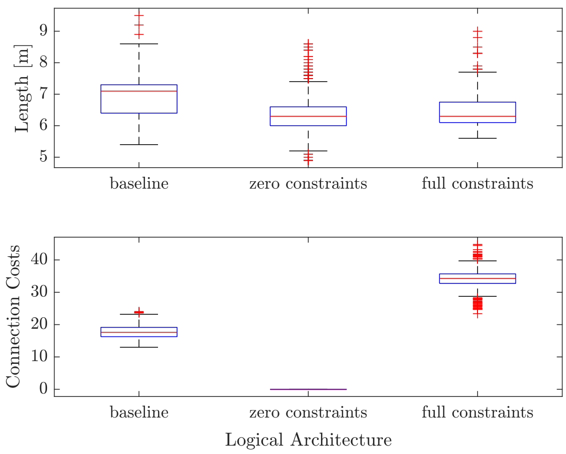

Figure 7: Variation of length and connection costs depending on the allocated connection matrices

Figure 8 shows that the distributions of the variables vary. The statistics of length and connection costs provided in Tables 10 and 11 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 alteration in PPE systems generates uncertainty in the design process and needs further investigation to minimize the risks propagated throughout the design process.

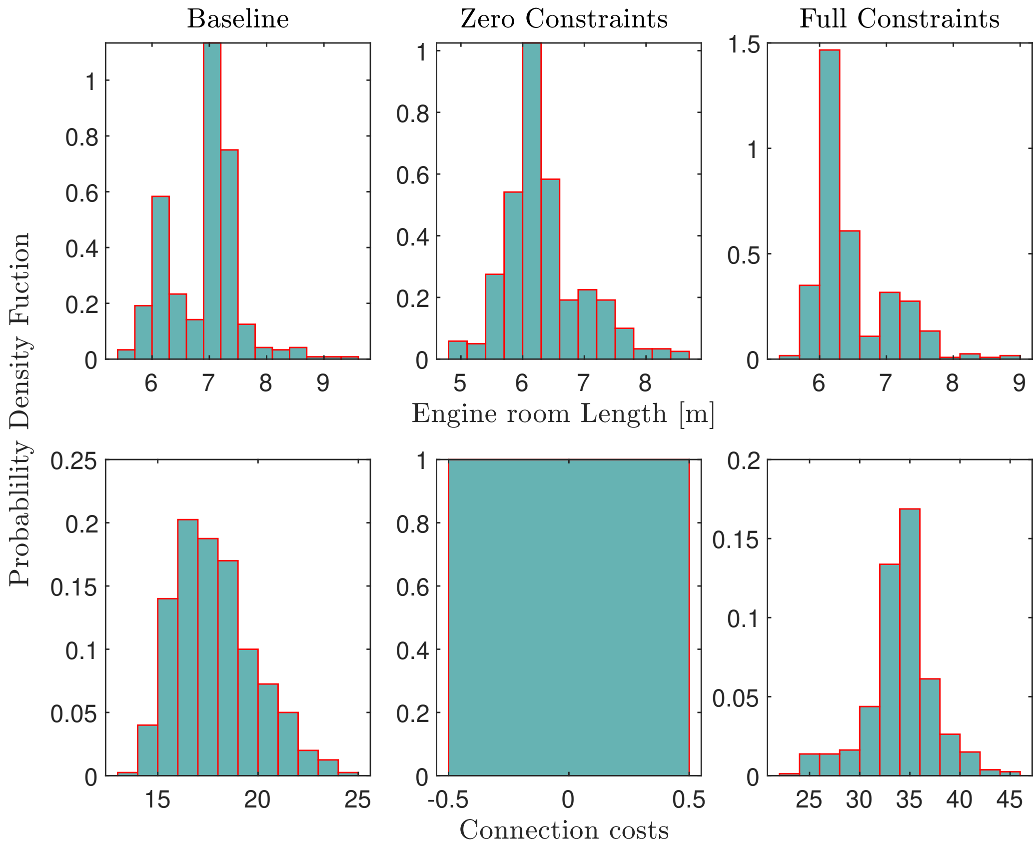

Figure 8: Length and Connection Cost distribution per different scenario

Table 10: Length [m] statistics per scenario

Measure	baseline	zero	full constraints
μ	6.91	6.39	6.49
σ	0.63	0.64	0.57
kurtosis	3.65	4.00	4.63
skewness	0.13	0.78	1.28

Table 11: Connection costs statistics per scenario

Measure	baseline	full constraints
μ	17.86	34.16
σ	2.01	3.29
kurtosis	2.95	4.51
skewness	0.60	-0.36

4.3 Discussion and Results

This study represents an attempt to study the influence of uncertainty in the design process due to the integration of alternative fuelled PPE systems. The integration of a multi-objective optimisation process in Monte Carlo simulations leads to increased computational modelling cost and complexity. For this reason, a simplified case study is developed to increase the ease of application. As discussed in Section 2, there is lack of knowledge regarding the actual size and shape that alternative fuelled PPEs are going to be,due to the technological advancements and the safety regulations under development. In combination with the case study, it is clear that there is no consistent pattern regarding the properties of the design space. The logical architecture in the form of the connection matrix proved a highly influential parameter that differentiates the design space more than the actual dimensions uncertainty.

In terms of the actual layout, margins for the BBs were included to account for possible corridors and safe spaces that need to exist within the engine room. The layout integration aims not to find the optimal configuration of the engine room, but instead to establish insights into the variation of the generated designs under uncertain conditions. It stands out that either *zero constraints* or *full constraints* lead to a smaller overall length, meaning that there is no linear behaviour depending on the number of constraints applied. Lastly, the method is not yet able to fully model the uncertainty propagation within all of MBSE layers and the case study was mostly limited to the physical and logical architecture layers.

5 CONCLUSIONS

The presented study establishes the uncertainties relating to power propulsion energy (PPE) systems that are generated from technical and regulatory factors. The review of the state-of-the-art in methanol fuelled vessels and the state-of-the-art on systems showed that more elements should be combined in the design process to fully understand the influence of the PPE systems on ship design. The uncertainties that were presented in Table 7 can prove critical design drivers. Based on these, a design framework is proposed (Figure 1), which centers around the inclusion of uncertainty and its propagation through the model-based systems engineering (MBSE) layers, as shown in Table 7.

Complementary to the review of the state-of-art, a case study is set up to evaluate the uncertainties within the physical space combined with different logical architectures. This case study investigates the effect of variable dimensions and connection costs of the building blocks on the overall size of the engine room. The outcome confirms the findings reported in the literature. The distribution shapes of the output variable differ from the uniform input distribution, meaning that the size alteration does not always prove to be fully influential. Furthermore, modifications to logical architectures result in distinct distribution patterns, leading to inconsistencies in the outcomes. Therefore, there is the need to gain a better understanding on the way that PPE systems are integrated into the vessel and the constraints imposed on the design because of safety or performance demands. Future research will therefore focus on the percolation of the established uncertainties within the layers of MBSE with a particular emphasis on understanding the effect of the different design choices on the overall design.

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