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Co-Design and Energy Management for Future Vessels

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Abstract

The maritime industry is undergoing a significant shift towards more sustainable and efficient forms of transportation. As a result, designing Power, Propulsion and Energy (PPE) Systems for future vessels presents new challenges that require a systematic approach that reduces the risk in development and implementation. This paper focuses on three aspects of such a systematic approach: Model-Based System Engineering (MBSE), Co-design, and Verification and Validation. The MBSE approach can be used to mitigate the risks associated with the transition by maintaining a clear traceability of user needs, functional requirements and physical realizations. A rigorous needs analysis and functional design reduces the optimisation design space that results in a significant reduction in the complexity of a design optimisation problem. Further, co-design is discussed as a methodology for a combined optimisation of the hardware and software design where the Modular Energy Management approach supports automated controller generation for the optimisation, a key challenge when optimising PPE systems. An important aspect of the MBSE approach is the use of models for the verification and validation of the developed designs. However, the successful use of models is contingent on their applicability. This paper proposes a way to categorise model confidence for verification and validation studies.

Keywords: PPE; MBSE; Co-Design; Energy Management; FMI.

1 INTRODUCTION

The use of fossil fuels significantly contributes to pollution and greenhouse gas emissions. To prevent further climate change, both the International Maritime Organisation (IMO) and the European Union (EU) have defined ambitious and compulsory targets for the reduction of emissions in the near future. The EU's objective is to reduce greenhouse gas emissions by at least 55 percent by 2030 and achieve climate neutrality by 2050 [1]. Similarly, the IMO aims to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40 percent by 2030, with efforts towards a 70 percent reduction by 2050, compared to 2008 levels [2].

Several regulations related to these targets have been introduced. The EU introduced the ”Fit for 55” package, which includes measures such as the Emission Trading System (ETS). The ETS enables the direct reduction of greenhouse gases by setting an overall emission cap per sector and enabling emission credits trading between partners. The revised Renewable Energy Directive (REDII) focuses on greening fuel production and distribution. Additionally, FuelEU Maritime aims to increase the share of renewable and low-carbon fuels in the maritime fuel mix. In parallel the IMO regulates the energy efficiency of newly built ships by means of the Energy Efficiency Design Index (EEDI) and the energy efficiency of operational ships with the Ship Energy Efficiency Management Plan (SEEMP). These regulations become progressively more stringent over time, with the aim of achieving greater emission reductions.

Clearly, the transition from fossil fuels to cleaner and more sustainable alternatives implies a big challenge for the maritime sector. The introduction of many upcoming regulations adds to the complexity, and their precise impact is now always in advance. Furthermore, there are many unknown factors to consider — Which fuels to choose? Which power & energy systems are suitable for my operation? How reliable are these new systems considering that many techniques are not yet fully mature? What emission reductions can we achieve and do the solutions comply with the upcoming regulations?

Given that this energy transition in the maritime sector is rapidly evolving, the conventional approach to design may not be sufficient to keep up with the pace of change. It becomes essential to adopt a ”first time right” approach and pursue parallel and multidisciplinary developments as much as possible. This paper aims to describe an ap-

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proach that addresses the forthcoming challenges in the maritime sector. At the core of this approach is Model-Based System Engineering (MBSE), which provides a well-structured methodology to reduce the risks during the development and construction of future vessels. By establishing a clear traceability of user needs, functional requirements, and physical realizations, MBSE enables early-stage risk reduction in the design process. Additionally, this approach incorporates verification and validation test plans that can be traced back to these needs and requirements, further enhancing the reliability of the vessel development process.

Furthermore, the majority of new low- or zero-emission fuels present challenges in terms of weight or volume. Consequently, future vessel designs will need to be optimised to accommodate these fuels based on user needs, while also optimising operational efficiency. The complexity arises from the interplay between these two aspects: optimised design and optimised operation. To address this challenge specifically in the Power, Propulsion, and Energy System, the paper proposes the utilisation of co-design. Co-design is a methodology that integrates the design of the physical system with the design of the control system. This integrated approach necessitates an automated method for generating an appropriate Energy Management strategy. The Modular Energy Management Strategy (MEMS) effectively fulfills this requirement. A case study from the automotive sector that demonstrates this approach is also presented. By incorporating MEMS within a co-design framework, supported by an MBSE-based approach, this article presents a solution to address the upcoming challenges in the maritime sector.

This approach will be explained in this paper. The application and demonstration of this approach will be subject of future publications. This work is part of the Methanol as an Energy Step towards Zero-Emission Dutch Shipping (MENENS) project which aims to make a significant impact on the Dutch shipping industry and reduce CO_2 emissions by laying out the framework for equivalent safe use of methanol as a fuel in commercial shipping that is cost-effective and sustainable [3].

2 THE MBSE APPROACH: CHALLENGES AND OPPORTUNITIES FOR MARITIME

2.1 The MBSE Methodology

MBSE applies models to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases [4]. MBSE replaces a document-centric engineering approach with a model that serves as a “single-source-of-truth”. As stated by Friedenthal *et al.* [5], “The output of the systems engineering activities is a coherent model of the system (i.e., system model), where the emphasis is placed on evolving and refining the model using model-based methods and tools.” This System Model or System Architecture Model is the hub for integrating data, engineering analysis, and simulation models used across the product life-cycle [6]. This integration improves consistency and traceability through the design process into operations.

The use of MBSE has several advantages. It results in more complete and consistent requirements when used for requirement development and engineering [7], [8]. The model-based approach can improve the design process by improving collaboration between stakeholders by providing a consistent model across domains and enabling multiple viewpoints from different perspectives [9], [10]. It improves quality by enabling rigorous traceability among requirements, design, analysis, and testing [11], [12]. Furthermore, it facilitates ongoing requirements validation and design verification from the early phases of a complex project [5], [13], [14]. All of these aspects reduce the risks associated with complex projects.

However, there are challenges in adopting the MBSE approach in organisations. Designers and engineers across all disciplines involved in the project need to understand the MBSE approach [15]. In addition, when working with a large diverse set of stakeholders across organisations, it is challenging to create a mechanism where stakeholders update the integrated architecture model rather than their own representations that they are used to [12]. Simpson *et al.* [16] stated that “The maximum benefit of employing a single integrated end-to-end description may only be realized if it serves as a single source of truth for capturing, representing, and communicating the description of the latest architecture design by the majority of the stakeholders involved.” Feedback from MBSE users shows that it remains difficult to create an accessible single source of truth for multiple, multi-disciplinary stakeholders. The risk is that MBSE tool users become experts and external stakeholders need them to translate the MBSE model content, making the MBSE model just another dataset. Another challenge is interfacing the system architecting tool to the existing tools being used in the design process. Many tools are already involved in the design, analysis, and testing of projects, and the integration of results from these tools in the system model should be automated to maintain consistency and prevent ambiguity by duplication. Despite these challenges, there is a clear advantage to applying the MBSE approach to complex projects. In a review, Carroll and Malina [7] reported a significant advantage in project performance by applying the SE/MBSE approach. They also report that an MBSE approach improves engineering efficiency and prevents costly rework.

The MBSE approach is built upon three pillars: modeling methods, modeling languages, and modeling tools/software, as illustrated in Fig. 1.

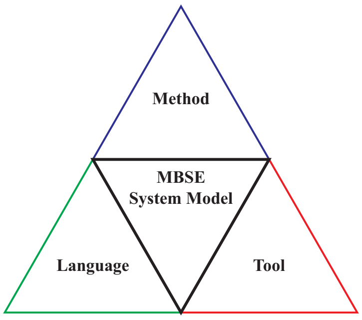

Figure 1: MBSE pillars. From [17]

MBSE Methods

MBSE modeling methods are conventions and step-wise procedures that describe the development and building of a system model. Methods usually define the amount of information and the sequence in which it is used. The most widespread MBSE modeling approaches are Harmony-SE, Object-Oriented System Engineering Method (OOSEM), System Modeling Method (SYSMOD), and Architecture Analysis & Design Integrated Approach (ARCADIA). Each of the listed methods has similarities to the rest but also unique characteristics. Some methods such as OOSEM are tool-independent, whereas others can be realized only with one specific tool.

MBSE Languages

A Model-Based Systems Engineering language refers to a specific modeling language that is used to logically describe and represent systems within the MBSE approach. Such a language provides a standardized set of notations, symbols, and rules for modeling elements and relationships that enable stakeholders to create and communicate system models without ambiguity. The most frequently-used MBSE languages are the Unified Modeling Language (UML) and the Systems Modeling Language (SysML), with the latter being an extension of the former. UML is applied in software engineering while SysML is better suited for systems engineering applications.

MBSE Tools

MBSE modeling tools are software platforms that enable the realization of the modeling procedures using the modeling languages. Tools provide user interface and may have a set of different functionalities, some being:

- Modeling and Diagramming - provide a visual environment for creating and editing system models using diagrams specific to the chosen modeling language. Commonly used tools are Capella, IBM Rhapsody, Cameo Systems Modeler, etc.
- Simulation and Analysis - system behavior analysis, system simulations, and assessment of system performance. Popular tools include MATLAB/Simulink and ANSYS.
- Requirements Management - management of requirements and dependencies. While IBM Rational DOORS is an example of a specialised requirement management tool, many modeling and diagramming tools are adopted for requirement management as well.

2.2 Application to maritime

Although models have been used extensively in the maritime sector, literature on the application of the MBSE approach is limited and most of these studies focus on naval applications. Poullis described prevalent ship design methodologies and explored the use of MBSE to address some of the shortcomings [13]. Furthermore, Tepper explored the use of MBSE in the design of the propulsion system for a naval ship [19]. The study highlighted the importance of beginning system architecture development at very early stages of ship design to ensure that the architecture is well-defined and addresses the needs of the stakeholders. Like experience from other industries, this study also identified the benefits of MBSE in enhancing communication, requirement traceability, and improved decision-making. Kerns *et al.* found that the complex relationships between systems and processes can be better managed by building a system architecture [20]. The system architecture can then be the single source reposi-

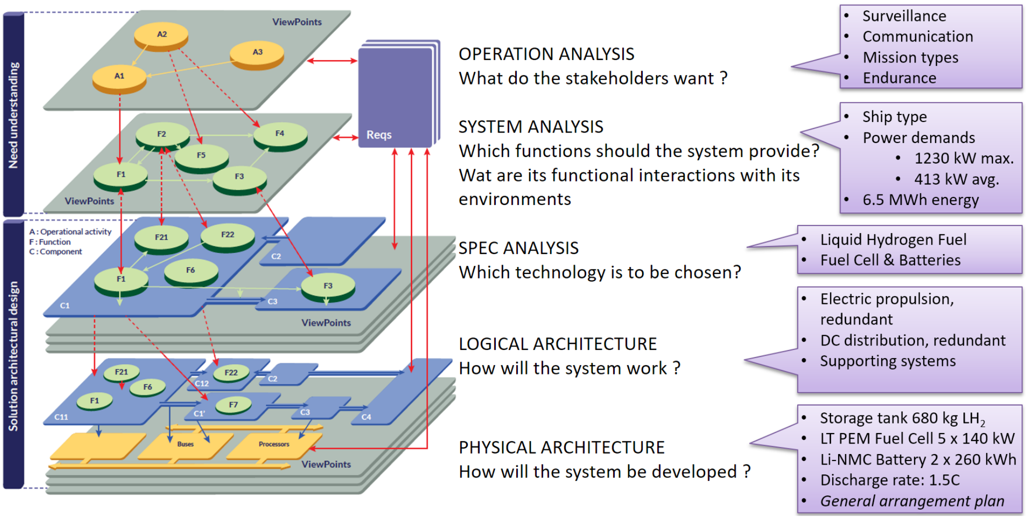

Figure 2: The Arcadia Capella MBSE approach (left) with its different steps (middle) and level of detail (right). The SPEC (Ship Power and Energy Concept) tool is a maritime sector design exploration tool that was integrated in the MBSE approach. From [18]

tory for all the information required for or produced by the ship design process. This was also found to be a useful tool for understanding the impacts of design decisions or changes on the physical design as well as on other aspects of the architecture like cost, function and capabilities. Similarly, Pearce *et al.* identified improved design consistency, precision, traceability, subsystem integration, and design evolution as key benefits attributed to the use of the MBSE approach [21].

More recently, the NAVAIS (New Advanced and Value-Added Innovative Ships) project used the MBSE approach in a modular system engineering-based ship design procedure [22], [23]. Veldhuis *et al.* reported the benefits of MBSE based design using a case study in [18]. The study used the Arcadia method in Capella for the Power, Propulsion and Energy (PPE) system architecture and requirements development for an Inland Patrol Vessel. Fig. 2 shows the structure of the method followed by the authors. The paper highlighted the importance of traceability and consistency in the design approach.

2.3 Lessons from other sectors

The maritime sector is not alone in its pursuit of MBSE and suitable methods towards a structured design process. One particular industry which as adopted and matured the MBSE approach is the automotive industry. Whilst there are many similarities in the challenges in this sector, it should be noted that not all of the manners in which the industry and market act is the same, and therefore a careful mapping of methods and solutions from this sector to maritime should be made.

For automotive, before model-based design, the development of new vehicles for the market would have gone through several prototype/mock-ups before series production. The onset of MBSE methodologies has reduced the need for full prototype development and testing. Tools and workflows such as utilising SysML have largely replaced the document-centered design process. Due to the relative scale of the industry, components (and models) have been standardised and modular solutions have been in focus for newer families of products.

The automotive development cycle traditionally follows a V-cycle, capturing the design process on the left, and the validation process on the right. The approach shown in Fig. 2 forms the left side of the V-cycle that results in a design in the form of a Physical Architecture. Due to the flexibility of the MBSE process, modern development also encompasses a V-cycle within the V-cycle wherein a virtual development loop is performed.

Within this inner V-cycle, the design is evaluated using virtual tests towards the compliance of specifications and requirements, as depicted in Fig. 3. This allows for optimisation of the design towards given criteria (such as cost, energy efficiency etc.). Several methodologies exist for virtually optimising the design of a system. One emergent technique highlighted in this paper, is that of co-design during this process. This is explained in the following section. Co-design is an emerging methodology finding place in both research and industrial contexts.

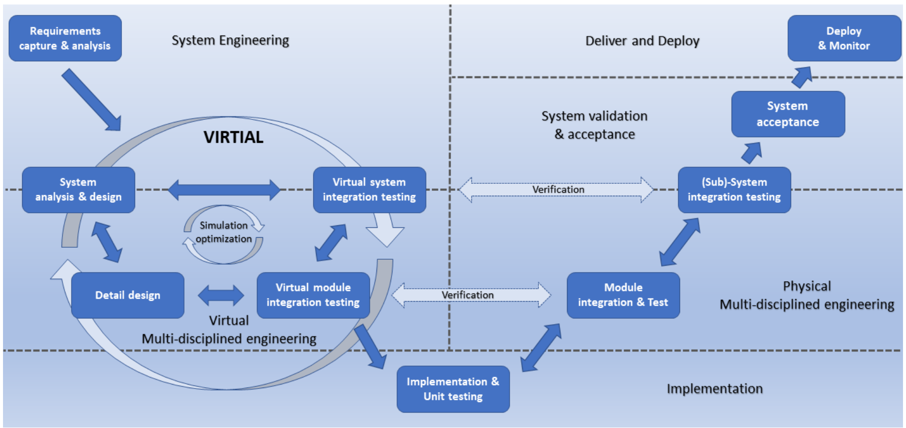

Figure 3: The new ”V in V” process - early and continuous feedback in early systems design phases.

3 OPTIMISED DESIGN OF PPE SYSTEMS USING CO-DESIGN

Although the MBSE approach brings structure and traceability to the design process, the technical challenges in designing an effective power and propulsion system are addressed by the co-design of component topology, sizing and controller. In this paper co-design refers to the specific aspect of the concurrent optimal design of plant (as topology or size) and control as reported in [24].

Co-design is a methodology that combines the design of the hardware of a system, alongside its control. In so doing, control techniques can be used to overcome the limitations of the selected components, whereas choices in the powertrain topology can enable improved control application.

For the design of the hardware, the first design space is for the selection of the logical connection of components (i.e. the topology), as illustrated in Fig. 4. In the next layer, the choice of what technology of the components is made, after which the components can be sized in relation to the requirements of the system. Finally, the inner-most level, the control methodology can be defined.

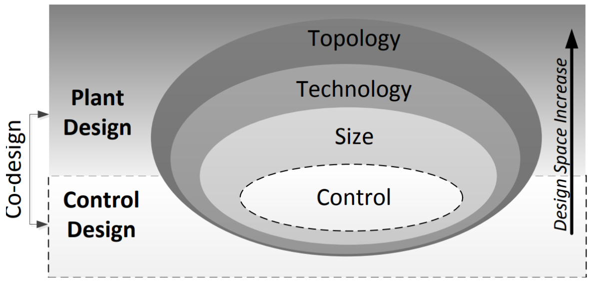

Figure 4: Co-Design Layered Approach. From [25]

It should be noted that there is some resemblance with the Arcadia method; in particular the Logical and Physical architecture from Arcadia match the Topology and Technology/Size layers in the Co-Design approach.

This layered view of system design can imply a nested approach to the design problem. The co-design methodology focuses on finding the optimal topology, sizing, configuration, and control of a power and propulsion system, based on a defined design objective function. The design objective functions are typically either a weighted equivalent function, or left open in terms of a multi-criteria approach.

Fig. 5 illustrates the availability of several variants of the co-design methodology. The most common co-design methodology exploits the alternating plant and control design architecture. Compared to nested and simultaneous schemes, this is seen to be more computationally efficient and easier to implement [25].

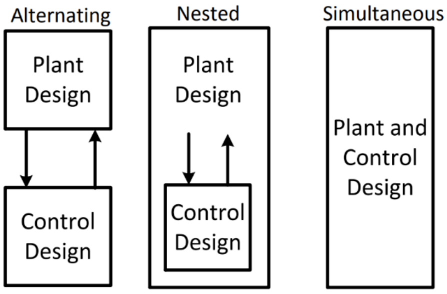

Figure 5: Co-Design Methodology Concepts. From [25]

Within an alternating co-design methodology, the plant design is fixed, allowing for the control design to take place at each stage. Once the control design is complete and evaluated, the results are used for the next iteration where the design of the plant is updated. Through an optimisation scheme, this methodology eventually converges into a plant and control design, which is measured as optimum and satisfies any requirements or constraints placed on the system.

For the maritime sector important optimisation objectives include fuel consumption, emission, system volume and weight, lifetime, and cost. These aspects are also important for other modalities such as automotive. The constraints are more maritime specific, focusing on on-board safety typically in harsh environments, sizing constraints because of hydrodynamics and stability aspects and specific Class Rules. However, an overarching maritime objective is de-risking of a design that uses innovative, less mature technologies. In maritime a prototype is often going into service and needs to be “first-time-right”. That asks for a robust solution with a clever balance of the optimisation objectives listed above. This also makes model-based verification and validation an important tool in de-risking the project.

The co-design approach represents an opportunity for virtual development and evaluation within the design process, representing a virtual V-Cycle within the usual V-Cycle of system development.

4 CO-DESIGN TOOLS WITHIN MBSE

To utilize co-design techniques effectively, the use of tools is necessary due to the typically extensive design possibilities. This section explores tools for plant modeling and control generation, both individually and in combination. It’s important to note that in this context, the terms ”plant” and ”system” are used interchangeably.

4.1 Plant/System

Modeling, simulating, and analysing the plant behaviour requires an MBSE modeling tool. One of the most popular software platforms in the automotive and maritime industries is MATLAB/Simulink. Simulink is a visual programming environment that allows for model representation through block diagrams, thus enabling the design and optimisation of complex plants. Plant models can be classified on the basis of the direction of physical causality used to simulate the plant. Two main categories exist - backward (reversed causality) and forward (established causality) models. Forward models represent the plant with high accuracy and are suitable for developing control algorithms, but require higher computational power and calibration. Backward-facing models require less effort to set up and simulate, making them ideal in cases where a sizeable design space has to be explored. However, such models lack the accuracy of the forward ones and often neglect dynamic effects and physical limitations.

Selecting the appropriate type of model is crucial and it is dependent on the development phase. Backwards models can be very useful during the initial design stages where the design space is relatively large. As the development is progressing it would be logical to use more accurate models that are relevant for more elaborate testing.

The QSS Toolbox by ETH Zurich is an example of a Simulink implementation of a backward-facing modeling library [26]. ADVANCE is a modular vehicle and powertrain simulation environment developed by TNO [27]. The Simulink-based forward-facing type vehicle and powertrain components allow for easy set-up of the vehicle of interest due to the standardized input and outputs.

The ship plant design process typically involves several stakeholders. Therefore, sharing simulation models across stakeholders who may be using different simulation platforms is a technical challenge but essential for consistency. The Functional Mock-up Interface (FMI) is an industry standard for model exchange and co-simulation across different simulation platforms [28], that promotes the MBSE methodology. Within FMI, models are exported in a standardized Functional Mock-up Unit (FMU) format, i.e. an ADVANCE powertrain model can be exported as a single FMU and reused in a vessel system model. By allowing for platform-independent integration of models from several stakeholders, FMI manages the complexity of large systems and promotes collaboration. The standard originates from automotive but it is widely used in various industries, such as aerospace, energy, etc.

4.2 Control

Automation plays a critical role in facilitating a purely computational approach within the Co-Design methodology, as highlighted in [29]. Specifically, during the control design phase, it is imperative to automatically generate the controller that effectively operates on the plant. Although heuristic rule-based approaches can achieve this, it is widely acknowledged that these control techniques may not produce the optimal solution against a control objective function.

In the automotive domain, various methods of optimal control theory have been applied for many years. However, defining, configuring, and calibrating these control regimes can be time-consuming and requires a high level of expertise from control engineers to implement reliably. As a result, rule-based control approaches have been dominant, and optimal control theory has yet to realize its full potential in the automotive domain.

The Modular Energy Management Strategy (MEMS) developed by TNO uses a dual decomposition to solve the Equivalent Consumption Minimization Strategy (ECMS) optimal control problem [30]. This innovative approach involves breaking down the optimal control problem into smaller subproblems, corresponding to subsystems or specific parts of the powertrain topology, such as the electric machine or the battery. By accurately modeling power flows within the system, MEMS ensures scalability and the ability to automatically generate solutions for various powertrain configurations, provided that the power balances at the nodes are known.

A crucial modification in MEMS, as opposed to ECMS, but equivalent, is that the optimisation objective involves minimising the total energy losses of each component. This redefined formulation allows for decomposition by considering the input and output powers of each subsystem.

The use of convex models to represent the powertrain components guarantees global optimality when the algorithm converges. To facilitate the automated generation of optimal control blocks, MEMS leverages a combination of a component library, an objective function, a component connectivity matrix, and a defined drive cycle. This streamlined process enables efficient generation of the control strategy in Simulink, making MEMS a powerful tool for optimising powertrain performance.

4.3 Plant/System & Control

Unlike plant modeling and control tools, few integrated plant and control tools for co-design are available. TNO has developed several powertrain co-design methodologies:

- TOPDSIGN - an automated tool for powertrain topology design and control, that aims at providing initial advice on the powertrain design and control for hybrid-electric vehicles [31]. The plant model is realized using the QSS Toolbox and it is controlled with MEMS.
- ADVANCE+MEMS - integration of an ADVANCE (forward) model and a MEMS controller within a co-design framework for (hybrid) electric vehicles [32]

4.4 Use-Case Study Co-Design

In this section, we consider a use-case of co-design applied in the automotive sector. The case considers the design optimisation of a hybrid truck, utilising the Modular Energy Management approach outlined in the European project ORCA [33]. The optimisation approach considered the sizing of key components in terms of maximum power, using a GA approach to find the optimal configuration for a given overall objective function expressed in terms of Total Cost of Ownership (TCO) [34]. It should be noted that the topology of the hybrid configuration was assumed, and as such the optimisation focused only on the control and optimal sizing.

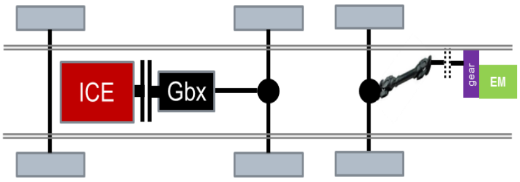

Figure 6: Schematic powertrain topology for hybrid truck [34].

The general approach was also considered by formulating the models within the co-design approach towards convex formulation, for a hybrid bus application [35]. The advantage of this approach is to guarantee global optimality of the optimisation approach. However, since the approach is a mixed integer problem (from the inclusion of gearing), the convex optimisation is combined iteratively with a dynamic programming approach.

Figure 7: Testing of the ORCA truck at the Vehicle Feature Lab [36].

Both approaches were ultimately used to govern the choice of hardware component sizes for two demonstration vehicles. These vehicles were assessed against the requirements formulated in the

MBSE approach through both virtual and physical testing, as illustrated in Fig. 7.

Such an approach that integrates MBSE, co-design for the optimisation of ship energy systems, and verification and validation can be benefitial in the maritime sector as well.

5 VERIFICATION AND VALIDATION

Using models to perform verification and validation testing through the design process can reduce project risks by identifying issues at early stages of the process. Simulation models can be used to test the requirements developed through the design process and ensure that the solution meets the user needs. However, as with the System Architecture model, the simulation model requires inputs and cooperation across disciplines and stakeholder which is a challenge. Furthermore, when working with multiple stakeholders on a common model, issues such as IP protection and the use of diverse modeling software and approaches often arise. While standards such as FMI described in 4.1 may offer a step towards a solution, it remains a challenge.

One essential aspect of using models within MBSE, is the understanding and confidence of their use from a verification and validation viewpoint. It should be recalled the clear distinction between the two, wherein [37]:

- Verification. The evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process. Contrast with validation.
- Validation. The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers. Contrast with verification.

When discussing the use of models, it is helpful to separate the concepts of the ’model’ in terms of the implementation of the equations in terms of code, and ’modeling’ in terms of the definition of how the physical system is represented by equations. Given this definition, it is possible to consider that a modeling approach might be novel, and therefore at a lower validity level, and where it has been implemented in code correctly. In that sense, the model can be less valid, but verified, and of course there can be situations where the converse is also true.

5.1 Model Confidence Level for Verification

As a way to categorise the level of verification of a model, the following classification is suggested in Table 1. Since the verification process is part of the model development, different types of virtual testing can be applied to verify that the model is correctly implemented.

Table 1: Verification Confidence categorisation.

Verification Confidence Level	**Short Name**	**Description**
1	Low	The code is implemented and executes, but not checked for valid output
2	Functional	The code is checked for a limited set of artificial functional tests, results are compared to expected outcomes
3	Domain	The code is checked within its domain of intended use, results are compared to expected outcomes
4	Independent	The code is independently verified with both functional and domain tests by third party

5.2 Modeling Confidence for Validation

In contrast to the model confidence, the modeling confidence represents the level of validity of the modeling approach. In general speaking, this is a measure of how widely the modeling method and representation of the physical system are accepted. Table 2 provides a suggestion for levels of categorisation for modeling confidence.

Table 2: Modeling Confidence categorisation.

Modeling Confidence Level	**Short Name**	**Description**
1	Novel	First of its kind, unproven technique
2	Adapted	Proven in one application, but applied in a domain where it is unproven
3	Adopted	Widely accepted technique, only partial evidence of real-world applicability
4	Proven	Widely accepted technique, validated through wide range of conditions and applications

5.3 Model Validation Confidence Level

After considering the modeling validity, and model verification, the level of confidence of the model validity needs to be determined. This is characteristically, that the model has been fitted with parameters for the specific system or component

Table 3: Model Confidence Level categorization.

Model Validation Confidence Level	Short Name	Description
1	Theoretical	The model is based on theoretical parameters/inputs only.
2	Derived	The model is based on a higher fidelity theoretical model.
3	Benchmarked	The model is based on or fitted against a matured simulation model
4	Empirical steady state lab	The model is based on experimental test data relating to steady state from lab tests in a narrow set of operating conditions, but combined with theoretical transient behavior and theoretical behavior in an extended range of operating conditions.
5	Empirical steady state lab extended	The model is based on experimental test data relating to steady state from lab tests in a wide set of operating conditions, but combined with theoretical transient behavior.
6	Empirical full lab	The model is based on experimental test data relating to both steady state and dynamic behavior in a wide set of operating conditions from lab tests
7	Combined	The model is based on subsystems that are individually validated to at least MCL 5-6.
8	Validated lab	The model is based on or fitted and validated against real-world emulated conditions within a lab environment.
9	Validated real-world non-domain	The model is based on or fitted and validated against real-world operational data for one application, but extrapolated for assessment in another.
10	Validated real-world domain	The model is based on or fitted and validated against real-world operational data for the relevant application.

which it represents, and that the combination of the modeling approach and fitted parameters adequately captures the designed accuracy required for the functional use of the model.

It is clear in this regard, that a model can be measured at different levels of validity. It is often useful to rank the level of model confidence. For system development, the confidence level of components can be high, but their combination as a system be at a lower level where the interactions of the models may be a source of inaccuracy.

A ranking system is suggested in Table 3, which can be referred as a Model Confidence Level (MCL). Since models by definition are a simplified representation of a physical system, it is important to track their validity through the design process. However, the availability of data for model validation, especially in the maritime domain, is a challenge.

5.4 Model Use through the MBSE Process

The MCL for components can be improved through the design process, or making use of preexisting library of components with high MCL from prior development. In the early stages, relatively simple models can be used which have limited numbers of parameters to fit/scale.

Where laboratory test data, or field operational data becomes available, the parameters of these models can be re-fitted improving the MCL.

Further, as component or controller hardware becomes available, these components models can be replaced in the following methods:

- MIL – Model-in-the-Loop. The functional testing to abstract the behaviour of a system so that the model can be used to test, simulate and verify itself. Often for control development
- SIL – Software-in-the-Loop. The testing of a compiled software component, wherein the loop comprises of a simulated system
- HIL – Hardware-in-the-Loop. The testing of a single component, wherein the loop comprises of a simulated system. Controller (PIL) can be part of the hardware or separate.

The latter of these methods, hardware-in-the-loop allows for critical hardware to replace models in the system simulation. These tests can be completed by the vessel developer, or the component supplier, provided that the interfacing between the simulation models and hardware is well defined. One of the challenges of working in this form, is allowing for a system model to be made available to suppliers, or conversely allowing for models to be made available by suppliers for evaluation.

6 CONCLUSIONS

The maritime industry faces new challenges in terms of design and development of future vessels, meeting new emission requirements, and increasing complexity of design and control. These systems mean that a systematic approach is required to virtual explore design options, set against the overall requirements and design objectives. Model-Based System Engineering (MBSE) is a strong candidate approach emerging within the sector, already used in other industrial segments.

This paper has presented the principles of the MBSE approach as an overview for the methodology required for complex vessel development. Where models are used, care needs to be placed on understanding their use in terms of verification and the levels of validation. Several ranking schemes are presented to indicate the level of confidence in the models being used.

Co-design is discussed as a methodology for optimising the design of the vessel in terms of both hardware and controller design, which yields high potential for complex system design. This methodology represents a V-cycle within a V-cycle for virtualised design and assessment. Finally, as a key enabling technology, the Modular Energy Management Approach is discussed, fulfilling the need for automated controller generation for a given plant design, as part of the co-design process. All that is put into context by presenting a use case from the automotive domain.

The use of the MBSE approach and the innovations presented in this paper still have challenges in terms of the widespread adoption. These are:

- A common approach for the handling of models and IP needs to be adopted between suppliers, vessel developers, and research partners.
- A willingness to share data, or validated models between stakeholders, with transparency over the validity
- MBSE approaches beyond the design process, extending into hardware evaluation via MIL and HIL methods
- Sharing of tools and methods from the research community to help accelerate the transition to MBSE

Overall, a strong and resilient maritime industry requires collaboration, and the tailoring of methods to the needs of the sector, and the tough emission targets ahead.

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