DESIGN METHODOLOGY STATE-OF-THE-ART REPORT

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ABSTRACT

Marine systems design methodology is continuously evolving. On a strategic level, we have seen four major evolutionary tracks emerging from the sequential, iterative process captured in the classical design spiral. One is a model-based systems engineering approach that removes iterations by a structured mapping from needs to functions, and further to form elements that are finally synthesized into a complete design. Another is a set-based strategy, where a large number of designs are generated and analysed, from which one or a few solutions are selected for further development. A third direction is a holistic optimization strategy where the major steps in the spiral model are integrated onto a common platform that enables the automatic identification of one or a few balanced, preferable solutions. Finally, as a strategy towards improved competitiveness through standardization in a typical engineered-to-order industry, we have seen the emergence of modular architectures combined with configuration-based design methods.

Across these four evolutionary tracks there have been several more focused developments on different levels of maturity. This includes design-for-sustainability, simulation of operations, design-for-flexibility to handle uncertainty and change, and design of wind-assisted vessels. Finally, we have pointed to some emerging developments that we find promising but have yet to mature into having a significant impact on industry-level applications. This includes artificial intelligence and machine learning, extended system boundaries, and digital twin technologies.

KEY WORDS

Design methodology; system-based design; set-based design,; design optimization

INTRODUCTION

The design methodology state-of-the-art (DM-SoA) report as part of the IMDC has a long history. Yet it has still to settle into a final structure, form and style. An excellent synopsis of the DM-SoA timeline from the start of the IM(S)DC until 2018 was given by Andrews et al (2018) at the Helsinki conference. This timeline shows a large variety of interpretations of what the SoA report at the IMDC should comprise, ranging from reviews of the ship design history, different variants of "Design-for-X" (e.g. X being safety (Vassalos 2012) as well as challenges related to the design of particular ship types, such as cruise vessel designs and LNG Carriers. The last DM-SoA report presented in 2018 contained three somewhat separate parts: First a review of three substantial books considered relevant for the design of complex marine vessels, followed by a review of selected design research activities, and finally a study of structural selection in early-stage design. Also, in the wake of the previous IMDC a comprehensive compilation of a wide array of research contributions within the field appeared as a RINA Special Edition authored by Andrews (2018), pointing towards a unique theoretical platform for marine systems design of complex vessels.

Recognizing the importance of the DM-SoA as a binding thread between the tri-annual IMDC conferences, and the so far lack of a clear consensus on style, form and structure was the background for bringing this issue on the agenda at the IMDC International Committee interim meeting at UBC in February 2020. A formulation of the DM-SoA goal and purpose was proposed, namely to "*analyse and summarize, on behalf of the marine systems design community, the current state and key developments within our field, based on a review of current research and technology achievements, as well as feedback from academia and industry*". Regarding form, style and structure, a set of characteristics were proposed. It should be *focused* on marine systems design, with a clear emphasis on *design methodology* within the larger framework of engineering design/systems design. It should be *contemporary*, giving priority to what have been key topic areas and achievements since

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the last conference, as well as ongoing research developments towards the next venue. It should be *opinionated*, to the extent that the authors of the report need to make an educated prioritization of what are the most important developments, as well as provide a basis for discussions and comments at the conference. Finally, it should also *balance* the focus between academia and industry and look into how research and technology developments are adopted in industry and actual design practice.

In this year's DM-SoA paper we have aimed at following up on these principles. The focus will be on recent and emerging developments as well as state-of-the-art, more mature methodologies applied by those design companies and shipyards that are at the technology frontier. We will also summarize recent research contributions based on journal articles, conferences, and research projects. Finally, we will point to emergent models, methods and technologies that we find promising, and where we would expect to see some more tangible results and piloting industrial applications towards the next IMDC.

DESIGN STRATEGIES – TRACKS AND DIRECTIONS

A *strategy* is a high-level plan for achieving an overall goal. Related to ship design methodology, it can be translated to the way we organize the design process from the initial capturing of customer needs and expectations until a final design solution is described and documented.

It may be useful to make a distinction between *descriptive* and *prescriptive*, or *normative,* design strategy models. Descriptive models are developed based on observations of how design processes are actually executed in an industrial setting, and subsequently capture and describe the important phenomena and relationships as objectively and accurate as possible. The classical ship design spiral is a good example. Initially it served as a normative model for how the ship design should be executed, by "balancing out" the conflicting requirements of the customer. Today the spiral is rather considered a *descriptive* model. Partly, it captures the sequential, iterative aspects of the design problem space, as such *characterising* this process rather than describing it. Partly the model represents at least some instances of actual ship design processes in many companies, that typically start with a catalogue vessel or a previous project to be sufficiently modified to fit the needs and requirements of a new customer. Thus, to the extent being descriptive, it is not a "one-size-fits-all" model as pointed out by Andrews (2018), p.2, but rather a common reference point for the discussion of alternatives, also in this paper. Today, most books, papers, tools and experts would *prescribe* alternative design strategies, typically pointing to the spiral model´s lack of concurrency and the inefficiency of a large number of iterations, its inclination towards the initial design proposal and limited coverage of the design space, and its "outside-in" direction that gives little support for deriving form from needs and functions. Still, we consider the spiral model a useful, commonly understood reference point for discussing alternative design strategies, regardless of its relevance for modeling real-world design processes.

Our proposition is that over the last decades we have seen four major evolutionary tracks emerging from the sequential, iterative design spiral model. One is a *model-based systems engineering* approach that removes iterations by a structured mapping from needs to functions, and further to form elements that are finally synthesized into a complete design. Another is a *set-based strategy*, where a large number of designs are generated and analysed, from which one or a few are selected for further development. In *configuration-based design* a customized design solution can be derived by combining modules from a product platform. Finally, we have seen an *optimization strategy* where the spikes in the spiral model are integrated into a common framework that supports the identification of preferable solutions by an optimization algorithm. These tracks are illustrated in Figure 1.

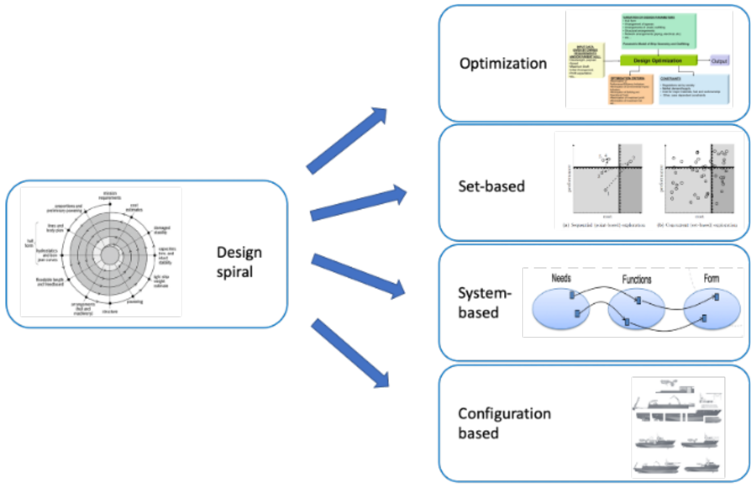

Figure 1: The four main design strategy directions emerging from the design spiral model

Later in this paper we will use this coarse sketch of high-level design strategies as a map for locating different research contributions in the design methodology landscape. We will observe that most of these contributions do not fall neatly into a single category. Rather, they will contain elements of several or all of these. For instance, in the building block approach (Andrews and Dicks 1997) we can have a system-based development of ship modules followed by a configuration-based synthesis into a set of alternative conceptual solutions. Or we can have a set-based approach exploring the design space and based on this derive a surrogate model that can be optimised by gradient search. It is safe to say that most comprehensive design methodology frameworks will contain at least traces of each of these categories. Thus, it is worthwhile expanding somewhat more on each of them.

System-based design methods/strategies

Though system-based ship design might sound like being a domain specific variant of systems engineering, it has more in common with the influence of the "German design school", most comprehensively described in the book "Engineering Design: A systematic approach" (Pahl et al. 2007). The systematic approach is basically a stepwise process from needs, via functions to physical solution principles and ends up with form elements that can be synthesized into a complete solution. Related to commercial marine systems design, the contributions by Kai Levander have had a major influence, developing this systematically over many years based on his work at the Kvaerner Masa Yards. The key element in this process, as compared to the more traditional approach, was to drive the volumes, areas and key characteristics of the main ship systems based on the combination of functional requirements and experience-based functions and coefficients. This replaced the not very well explained process on arriving to the initial design solution in a spiral-based approach, and instead prescribed a series of abductive logical steps in which all the main components of the solution were mature in terms of areas, volumes and capacities. This process is somewhat similar to a set of Lego bricks that could be combined towards many possible conceptual solutions while still representing a balanced solution. Thus, in the subsequent synthesis steps towards a complete form, the focus is shifted from "balancing out" requirements, to a focus on the overall conceptual solution and arrangement optimization. Further, this approach represents what is often referred to as an "inside-out" methodology, by first developing and arranging all internal systems and volumes of the ship, and finally wrapping a hull around this assembly. The process is illustrated in Figure 2, where we see that though the initial design should be derived systematically from needs via function, there will still be a need for a "spiral-like" sequential, iterative "outbalancing" of the vessel to converge.

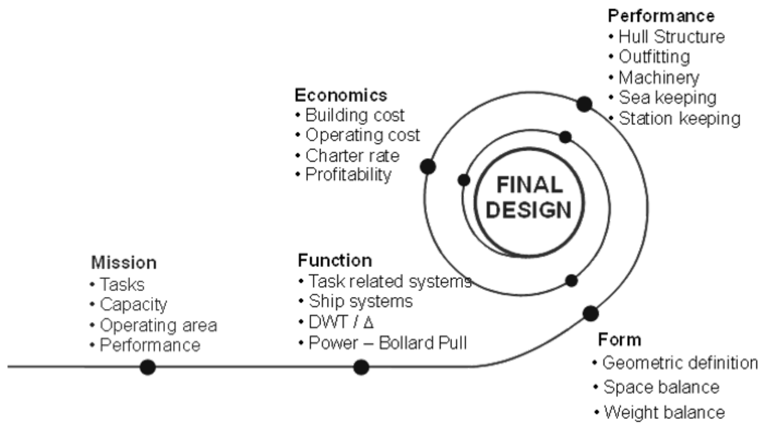

Figure 2: System-based ship design, unwinding the first loops of the spiral to achieve an improved initial solution based on systems thinking, from (Levander, 2006)

Similar to the system-based design model from Levander, the Design Building Block approach proposed by Andrews and Dicks (1997) promotes a shift to the early stages. This method supports the difficult balance of on the one hand making the design problem tractable by developing the necessary form elements as building blocks that each deliver one or a few required functionalities, while on the other hand keeping the problem sufficiently open to explore and analyze alternative conceptual solutions, system architectures and various aspects of "style". This is closely connected to the concept of "requirements elucidation" presented by Andrews at the IMDC Athens conference (2003b), pointing to the simple fact that in real-world design processes the customer does not come to the table with a set of well-stated, optimal requirements, nor would the customer have a rational basis for determining those without exploring what capabilities that can be achieved within the budget constraints and economic reality of the business case or naval acquisition program. The importance of understanding the needs and expectations of key stakeholders has been further elaborated in the keynote paper by Brett and Ulstein at IMDC in Tokyo (2015), with their paper "What is a better ship? It all depends …".

We also find many of the more recent contributions and development relevant for this DM-SoA paper to have strong links to the system-based design strategy. The "packing approach" first introduced by van Oers et al. (2007) and continued by Duchateau (2016) emphasized the exploration of a design space formed by legal combinations of blocks or modules given a set of configuration rules and arrangement-related performances, thus combing a system-based, set-based and configuration-based approach. More recent contributions from Garcia Agis (2020) emphasizes the uncertainty related to the decision-making context of key stakeholders, while Ebrahimi (2021) points to perceptual and decision-making complexity as important factors.

Set-based design strategies

The use of set-based design (SBD) strategies for the maritime industry, specifically naval ship design, gained increased attention from the late 90s, with the University of Michigan being the focal point. According to Singer (2009) the inspiration was based on Toyota's design process for automobiles and built of four basic features: a broad set of parameters, keeping these parameters open until late in the design process to allow for trade-off studies, a gradual narrowing of the set towards an optimal solution combined with an increased fidelity level of the model. The SBD model was tested for its applicability in ship design in a series of projects at the University of Michigan around 2000. The conclusion was that this strategy performed better than point-based methods ("spiral") and optimization-based methods. Set-based design strategies have received considerable attention in naval ship design, with recent contributions from Doerry et al. (2019) on SBD used in acquisition processes, Gray et al. (2018) for upgradability studies and Rapp et al. (2018) for tradespace analysis of naval vessels.

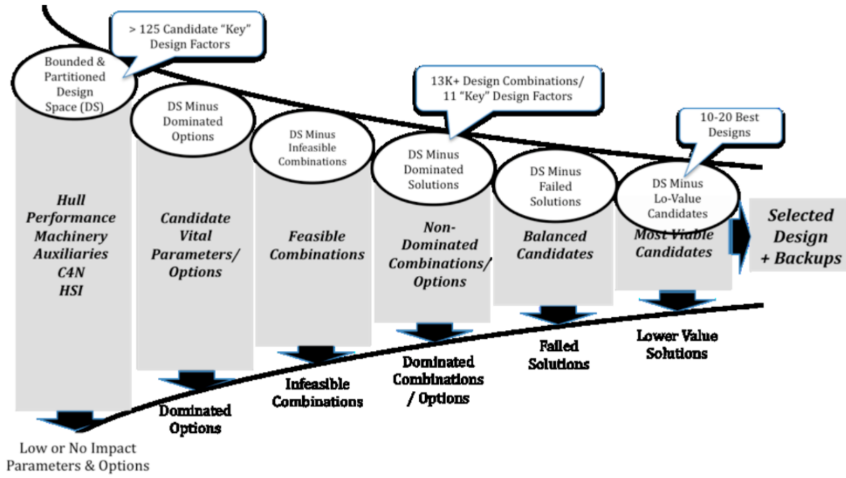

Figure 3: Down-selecting the solution space in set-based design, from McKenney et al. (2012)

Optimization-based design methods/strategies

Inherent in design is to find the *best* possible solution that will meet key stakeholders needs and expectations, which implies that design can be framed as an optimization problem. Still, considering real world design processes, optimization-based design processes are not very common, at least not in a classical mathematical programming framing. The main problem is simply that the typical ship design problem is too complex to be efficiently and accurately captured within the relatively strict boundaries of an optimization model. As said by Coyne (1990, p. 19): *Optimization has failed to influence the field of design greatly, in part because it does not address the question of how to arrive at such well packaged formulations.*

A recent effort to overcome these challenges has been the HOLISHIP project (Papanikolaou 2019). The objective of this project has been to integrate all main ship design disciplines into an integrated software platform that enables parametric, multi-objective optimization of the vessel design. Two of the strengths of the HOLISHIP project is that it is predominantly based on commercially available software, and that maritime industry partners have been actively participating in the project group. HOLISHIP builds on a long series of optimization-oriented projects, with a variety of overall design objectives. Examples are SAFEDOR for risk-based design optimization, GOALDS for RoPax and cruise safety, BEST for tanker environmental performance and SHOPERA for tanker hull form, to name a few.

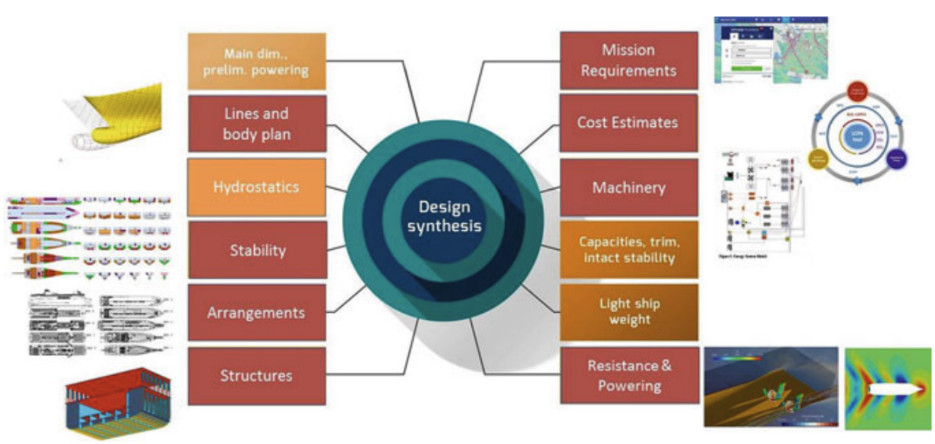

Figure 4: The main structure of the HOLISHIP project, (Papanikolaou, 2019)

Configuration-based design strategies, product platforms, "design for modularity" and system architecture driven design

By using configuration-based design strategies based on product platforms, it is possible to combine the requirements for customized solutions with standardization on a module or component level. Compared to other industries such as automotive and aviation, shipbuilding remains a typical "one-of-a-kind", "engineered-to-order" industry. A modular design strategy concurrently supports standardization and diversification on the product level, and has the potential to reduce cost and shorten development time, Erikstad (2019).

Configuration-based design requires a modular design architecture. From a wider systems perspective, modularity is a strategy for handling complexity by encapsulation, Simon (1996). This strategy is characterized by subdividing the larger system into smaller parts with a high degree of self-sufficiency, and the recombination of these parts into multiple end products. This recombination of parts corresponds to the synthesis process inherent in engineering design, which may be governed either by rules that define allowable re-combinations (Brathaug et al., 2008), by "style" that defines patterns of alternative product solutions (Andrews 2018), by the direct "creative" interaction with a designer, or by a combination of these.

Configuration-based design decouples the design process into two separate stages. First, a platform development stage in which the modules are defined and developed and integrated into a product platform. Second, a "configuration-to-order" stage in which individual designs are derived from the platform, customized to each end-users specific needs, (Erikstad 2019).

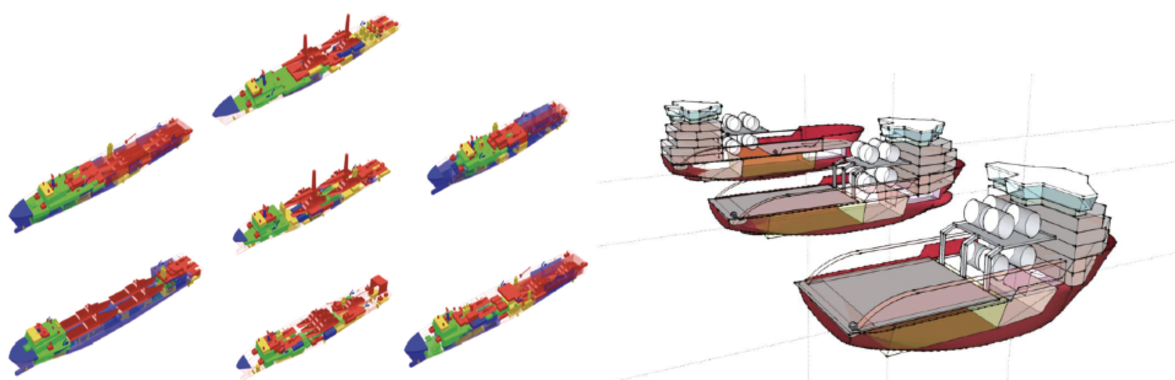

Figure 5: Ship designs based on modular configurations from a product platform-based architecture, left from Andrews 2011, right Vestbøstad 2011)

Recently, we have seen several interesting contributions on configuration-based design. Pfeifer et al. (2020) have developed a product platform for high-speed electrical ferries, in which standardized, reusable modules are identified using model-based system engineering methods. Choi et al. (2018) have developed a product platform combined with an optimization-based approach for designing modular adaptable ships. Here, the modular design configuration also considers the need for flexibility in the operational phase of the ship lifecycle to adapt to changing contextual circumstances that are uncertain in the design phase.

The four "strategic directions" for marine systems design pointed out here provides us with a map that is useful for navigating among the many research contributions in this field. Most of the methods and models proposed cannot easily be placed into a single one of these strategies, but rather contain elements from several or all. For instance, the interactive evolutionary concept exploration method from TU Delft (Duchateau 2016, van Oers 2011) resembles a system-based development of arrangement modules, a set-based exploration of the design space over a 3D GA configuration model, and with the definition of high-level objective functions and constraints similar to optimization. The modular adaptable ship design method by (Choi et al. 2018) is combing a platform architecture with an optimization-based configuration process. And the holistic ship design optimization (HOLISHIP) process by Papanikolaou (2019) also includes design space exploration aspects. Thus, rather than representing mutually exclusive categories, these high-level strategies rather serve as an indication towards what specific aspects a certain design method is emphasizing.

SOA AND KEY DEVELOPMENTS WITHIN SELECTED AREAS

In the previous section the focus was on the state-of-the-art of high-level design strategies. In this section we will go into the details of a few selected topic areas in which we believe we have seen the most interesting development and contributions since the last IMDC conference. Adhering to the general principle that "less is more", there obviously will be deserving topic areas that will be omitted.

The first selected topic, sustainability, is perhaps the one highest on the agenda for most stakeholders in the maritime community, namely, how to respond to the challenge of global warming, and meeting the targets set by IMO towards 2050. This will require new designs comprising new technology. The crucial question in the context of this paper is whether designing for sustainability will also influence *how* we design. Further, and keeping in mind that we are always designing for the future, we have seen a development towards explicitly integrating uncertainty and flexibility into the design process as a consequence of the fact that today´s technology is not capable of providing a "licence-to-operate" for new vessels under expected emission requirements towards the end of their design life. This is followed by design for safety, and the corresponding wider topic of risk-based design.

We have also seen that realizing the next generation of low or zero emission solutions will require that we shift the focus from exclusively on the vessel design itself into a wider system perspective that includes the concurrent design of vessels, concepts of operation and infrastructure and external resources. This is accompanied with system-level simulation of operations as a means for assessing complex performance parameters. As a final topic we have included wind-assisted ship propulsion (WASP). It can be argued that specific technologies or analysis models are not within the scope of a design methodology SoA. However, WASP is a good case for illustrating how technologies still under development could be included in a more mature design process, as well as requiring both the consideration of operational concepts and a simulation-based platform to fully assess the system level performance.

Design for sustainability

As for other DfX categories, such as design-for-production, design-for-safety, etc., design-for-sustainability is primarily about focusing on a particular set of high-level performance aspects related to three "pillars": environmental, economic and social. DfX categories will necessarily put requirements on the *content* of the design process, such as specific analysis methods for quantifying relevant performances (say, emission footprints), as well as the inclusion of new technology solutions, especially related to ship powering and fuel systems.

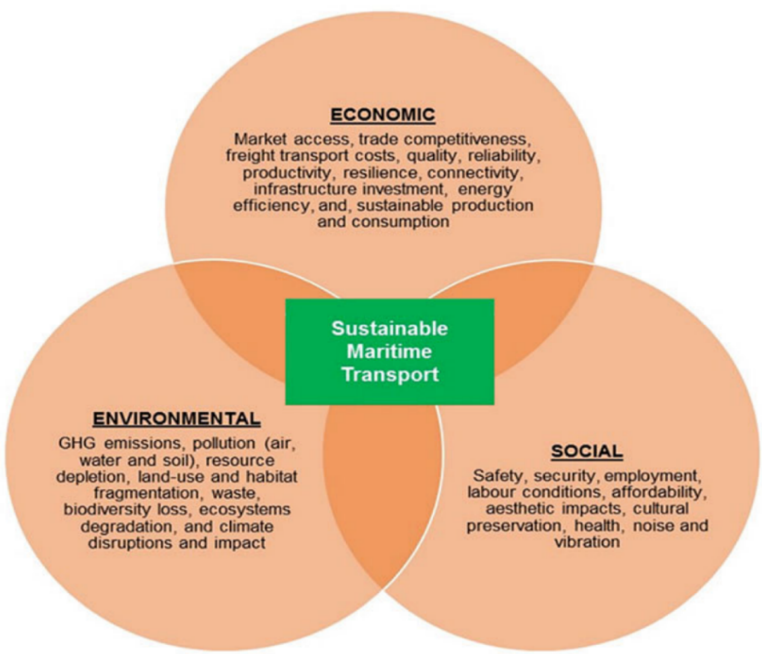

Figure 6: Sustainability pillars (source: Psaraftis 2019, reproducing UNCTAD 2015)

The relevant question from the perspective of this SoA paper is whether the introduction of this DfX category has spurred changes also from a design methodology point-of-view. Even though specific design and decision-support methods for groups of technologies, such as alternative fuels, are developing along with case studies and important pilot applications in industry, we currently perceive a methodological gap when it comes to sustainable marine design. The challenge is not only grasping today's design space to a fuller extend while simultaneously elucidating requirements, but also to design for likely future change(s). Sustainability is driven by both concrete requirements for newbuilds at present, such as the global Sulphur cap or EEXI and EEDI requirements, as well as long-term decarbonization strategies (e.g. IMO 2018). The longer the time horizon, the more uncertainty is brought into the game: Neither are technologies, regulations nor economic incentives fully in place today to meet future decarbonization requirements. We need to design for change in one way or the other, and hence many of the methods presented in the next paragraph are highly relevant from a sustainability perspective. In addition, taking a larger system perspective which includes fleets instead of single ships and infrastructure is gaining importance.

An excellent state-of-the-art paper on sustainable ship energy systems was recently published by Trivyza et al. (2022). Based on a comprehensive list of nearly 170 relatively recent papers, they summarized the needs for further developments into design methods by four points: 1) methods for developing potential solutions, 2) methods to assess the performance of alternative design solutions, quantifying energy efficiency and their mitigation potential, 3) methods to understand the impact of future uncertainty on the lifecycle performance of systems, including the generation of scenarios, and LCA, see Wang and Zhou 2018 and 4) methods for selecting among the different alternatives. The latter includes optimization-based approaches as well as multi-criteria approaches, see Frangopoulos and Keramioti 2010, also Mansouri et al. 2015. Lagemann et al. (2022) present a method for deciding among alternative fuels with given fuel price trajectories over the lifetime. Mestemaker et al. (2020) investigate the overall system integration of such alternatives and energy conversion options in more detail.

In general, we see that sustainability is receiving increasingly attention as a design driver and performance criterion in the design process (Papanikolaou 2010; 2019). It has certainly brought forward specific methods for assessing this criterion and selecting among innovative and emerging technologies, such as alternative fuels and wind assisted propulsion concepts, as well as life cycle perspectives receiving increased attention in the design process.

Design for uncertainty and flexibility

As mentioned previously, we are always designing for the future, and the future is inherently uncertain. The outcome of the ship design process is necessarily affected to a certain extent, whether we choose to explicitly address this uncertainty or not. Garcia Agis (2020) finds that regulatory, stakeholder expectations and economic uncertainties are overall perceived as the most influential uncertainties. Both regulatory and economic uncertainty are strongly linked to time, while stakeholder expectations hints towards lacking requirements elucidation (Andrews 2003; 2011).

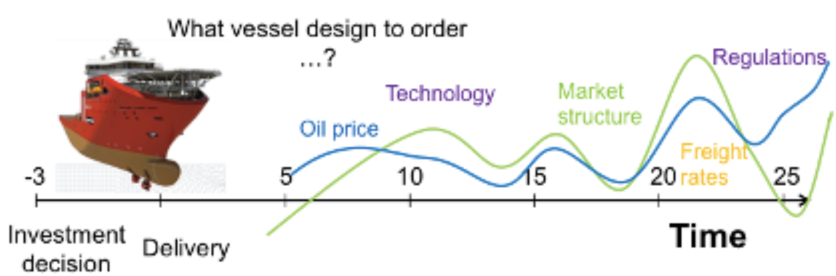

Figure 7: We are always designing for the future, and the future is inherently uncertain

The different methods for explicitly handling uncertainty in the design process typically share the following aspects. First, there is a need to effectively capture and model the relevant future operating context, as a set of scenarios. This may include markets (e.g. fuel prices, freight rates), technologies, regulations and physical environment. Then, within this set of alternative scenarios, we need to model and simulate the operations of the system to be designed in order to derive the technical, economic, environmental and safety performance in a lifecycle perspective. One of the challenging parts is to link those operational scenarios back to design decisions today, both related to "classical" ship characteristics, as well as quantified lifecycle performances such as flexibility, adaptability, versatility and robustness. Finally, all these steps need to be integrated into a holistic system design process.

De Neufville and Scholtes (2019) give a comprehensive overview on flexibility in engineering design and suitable methods. Rehn et al. (2018) find that changeability/flexibility can be a suitable strategy to respond to time-affected uncertainties and is hence worthwhile discussing in the early design phase. Within an extensive report, Schank et al. (2016) provide a naval perspective on flexibility and modularity. Choi et al. (2018) apply the concept of modularity to offshore service vessels. Based on a common platform, a configure-to-order strategy enables to quick response to varying customer mission requirements. Similar to Rehn et al. (2018), they find that reconfigurability through modularity can be of significant value under uncertain lifetime circumstances, such as changing ship missions or requirements. When designing flexible systems, agility, as a parameter denoting the ease of change, needs to be determined.

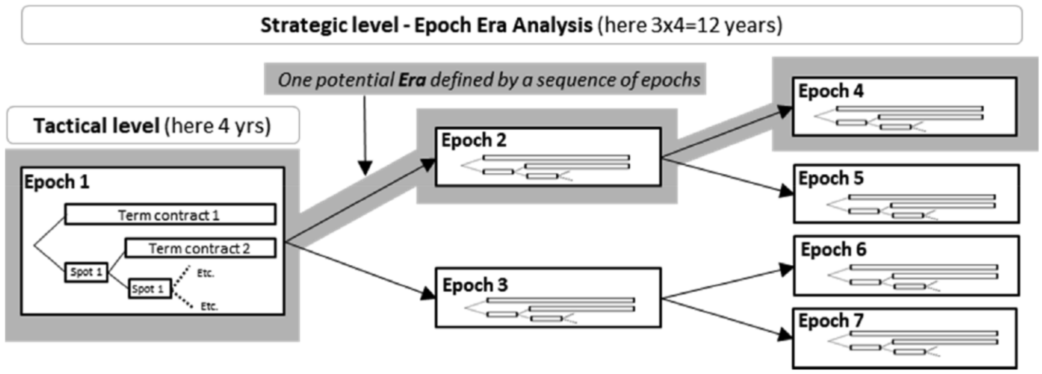

Figure 8: Designing for different future, taken from Rehn et al. (2018)

Design for safety

Safety has been a recurring theme throughout the past IMDC conferences (Papanikolaou et al. 2009). With stability accidents responsible for the largest share of fatalities, the topic is still highly relevant. The introduction of the second-generation intact stability criteria has impacted requirements but also spurred the development of tools (Petacco et al. 2021, Wang et al. 2020). On the damage stability side, dynamic simulations of damaged ships have gained attention (Vassalos 2022). The principal of equivalent safety can lower the required damage stability for autonomous ships (Vos et al. 2020). A similar probabilistic concept has been applied to fire safety of passenger ships by (Koromila et al. 2018). A design method for the safe-return-port regulation is presented by Valcalda et al. (2022).

Simulation of operations

Simulation as a tool for ‘unveiling knowledge’ (Simon 1996), is becoming increasingly integrated into the design process. To name a few recent developments:

- Based on the work of Sandvik et al. (2018), Dæhlen et al. (2021) the development of a voyage simulation tool that enables time-efficient comparisons of several designs.
- Open simulation platform (OSP): co-simulation of onboard systems (mechanical, electrical, control) (Perabo et al. 2020)
- Coupling of simulation and optimization in a design of a short-sea feeder network (Medbøen et al., 2020).

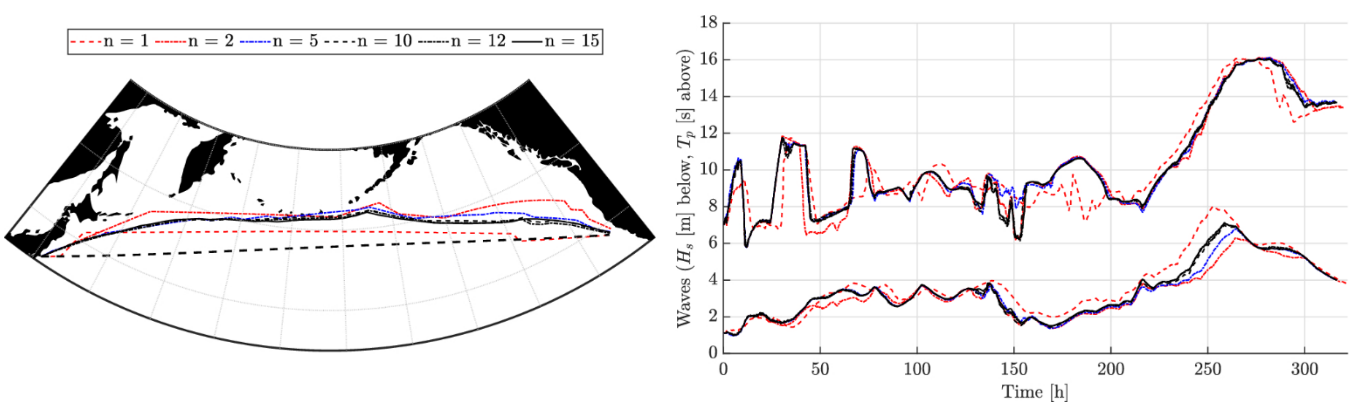

Figure 9: Voyage simulation for different route generation parameters, from Sandvik et al. (2020)

Coupled with virtual prototyping, we see simulation increasingly used as a tool in the design process. Simulation fidelity is application-dependent: Discretization may range from milliseconds (e.g. electric systems dynamics) to hours (e.g. voyage simulation) and needs to fit the purpose (effectiveness) and resources (efficiency). Moreover, the open simulation platform (www.opensimulationplatform.com) indicates that distributed simulations are developing, with individual systems running at separate locations and connected online.

From a design methodology perspective, we see an emerging need for operational system-of-systems simulations, that includes ships, infrastructure, fleets, and supply chains. The following section on WASP is one specific example that will require simulations. Our understanding of such larger systems is still limited. Simulation can be used as tool for 'unveiling' the required knowledge to meet either changing overarching system requirements or simply meet the same requirements in a very different way.

Design for wind-assisted ship propulsion (WASP)

Herbert (1980) describes the fundamental challenges of wind-powered ships as robust and efficient rig design (aerodynamic lift-drag ratio) and efficient hull design (hydrodynamic lift-drag ratio) within economic constraints. Arguably, the economic constraints may be challenged and perhaps changed as part of a result of thorough requirements elucidation (Andrews 2003; 2011). However, technical challenges and system interdependencies (see Figure 10) ultimately remain. Thus, specific methods are developed for the design and analysis of WASP: An integrated simulation model is used to account for and resolve the various interdependencies such as drift, heel or auxiliary power consumption (e.g. van der Kolk et al. 2019; Tillig et al. 2020; Reche-Vilanova (2021). Kramer (2022) presents an open-source CFD simulation for the hydrodynamic part of the equation. A useful collocation of scientific papers on various aspects of WASP can be found on (https://www.wind-ship.org/en/research/).

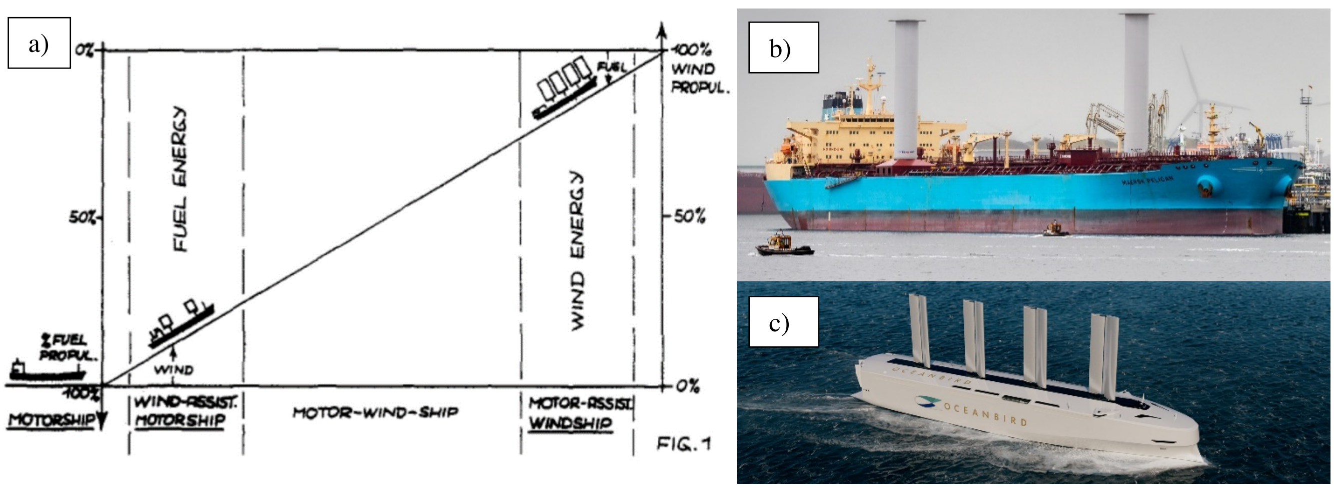

Figure 10: a) range of wind propulsion options, taken from Schenzle (1985); b) wind-assisted motorship; c) motor-assisted windship, courtesy of Oceanbird

Figure 10 illustrates the range of wind assistance, between a few percentage fuel savings up to 100% wind propulsion. While the aforementioned system performance prediction tools are needed for any type of wind-assisted ship, higher fractions of wind assistance will require a rethinking of the transport system design and possibly an extension of the system boundaries (Hagen and Grimstad 2008). For a higher uptake of WASP, the requirements imposed on a fleet or single ship need to be revisited to answer questions like:

- Is it possible to lower the average speed to allow for higher assistance of wind? If so, what is a minimum speed requirement?
- How much variation/flexibility do we allow for in the voyage schedule? What is the effect on the overall transport chain?
- Do shipping contracts need to be changed?

Simulating fleet operations may help answering addressing some of these issues and build confidence in innovative and fundamentally different system solutions. We think that a lot of design work on a system/fleet level, in addition to components, is still do be done for wind to become a viable power option.

SOA RESEARCH IN PRACTICE: A SELECTION OF RECENT PHD SCHOLARSHIPS

Similar to the last SoA report at the IMDC 2018, Table 1 attempts to provide an overview of recent developments by means of published PhD theses we consider having a clear marine design focus. The timeframe covered is basically since the Helsinki conference, but we have included some that were completed slightly before as well. We have categorized these PhD projects according to the four general design strategies, namely optimization (Opt), system-based design (Sys), set-based design (Set) and configuration-based design (Con), acknowledging that this classification might be both inaccurate and imprecise. To provide a quick idea of the topic, we additionally assign key words. The table is organized chronologically.

Table 1: Recent PhD scholarships related to marine systems design

Name	Title	Design strategy	Key words
Etienne Duchateau 2016	Interactive evolutionary concept exploration in preliminary ship design	Set, Con (Opt)	3D arrangement concept exploration
Francesco Baldi, 2016 (Chalmers)	Modelling, analysis and optimisation of ship energy systems	SysB	onboard energy systems
Ian Matthew Purton, 2016 (UCL)	Concept Exploration for a Novel Submarine Concept Using Innovative Computer-Based Research Approaches and Tools	Set, Con	submarine design
Ties van Bruinessen, 2016 (TU Delft)	Towards controlled innovation of complex objects. A sociotechnical approach to describing ship design	Sys	innovation management
Peter de Vos, 2018 (TU Delft)	On early-stage design of vital distribution systems on board ships	Opt, Sys, Con	system topology
Dorian Brefort, 2018 (Michigan)	Managing Epistemic Uncertainty in Design Models through Type-2 Fuzzy Logic Multidisciplinary Optimization	Opt, Set	optimization under uncertainty
Carl Fredrik Rehn, 2018 (NTNU)	Ship design under uncertainty	Set, Sys	design for flexibility
Minjoo Choi, 2018 (NTNU)	Modular Adaptable Ship Design for Handling Uncertainty in the Future Operating Context	Con, Opt	design for flexibility, modularity
Sigurd Solheim Pettersen, 2018 (NTNU)	Resilience by latent capabilities in marine systems	Sys	latent capabilities
Syavash Esbati, 2018 (UCL)	Design for Support in the Initial Design of Naval Combatants	Set, Con	3D arrangement, -ilities
Endre Sandvik, 2019 (NTNU)	Sea passage scenario simulation for ship system performance evaluation	SysB	simulation of operations
Nikoletta Trivyza, 2019 (Strathclyde)	Decision support method for ship energy systems synthesis with environmental and economic sustainability objectives	Opt, Con	decarbonization
Alexandros Priftis, 2019 (Strathclyde)	Multi-objective robust early stage ship design optimization under uncertainty	Opt	optimization under uncertainty
Etienne Gernez, 2019 (Oslo)	Human-centered, collaborative, field-driven ship design: implementing field studies for the design of ships in operation		UX design
Nikolaos Kouriampalis, 2019 (UCL)	Applying Queueing Theory and Architecturally-Oriented Early Stage Ship Design to the Concept of a Vessel Deploying a Fleet of Uninhabited Vehicles	Set, Con	fleet design
Linying Chen, 2019 (TU Delft)	Cooperative Multi-Vessel Systems for Waterborne Transport	Sys	logistics
Michael Sypaniewski, 2019 (Michigan)	A Novel Analysis Framework for Evaluating Predisposition of Design Solutions through the Creation of Hereditary-Amelioration Networks Derived from the Dynamics within an Evolutionary Optimizer	Opt, Set	design methodology
Lauren Claus, 2019 (Michigan)	Design Space Covering for Uncertainty: Exploration of a New Methodology for Decision Making in Early Stage Design	Opt, Set	optimization under uncertainty

Conner Goodrum, 2020 (Michigan)	Conceptually Robust Knowledge Generation in Early Stage Complex Design	Set	Knowledge-based design
Helong Wang, 2020 (Chalmers)	Development of voyage optimization algorithms for sustainable shipping and their impact to ship design	Opt	simulation
Wo Peng, 2020 (UCL)	Decarbonising coastal shipping using fuel cells and batteries	Sys	decarbonization
Jose Jorge Garcia Agis, 2020 (NTNU)	Effectiveness in Decision-Making in Ship Design under Uncertainty		design process management
Fang Li, 2020 (Aalto)	Numerical simulation of ship performance in level ice: evaluation, framework and modelling	Sys	simulation
Agnieta Habben Jansen, 2020 (TU Delft)	A Markov-based vulnerability assessment of distributed ship systems in the early design stage	Set	vulnerability of distributed systems
Fabian Tillig, 2020 (Chalmers)	Simulation model of a ship's energy performance and transportation costs	SysB	simulation of operations, decarbonization
John Marius Hegseth, 2021 (NTNU)	Efficient Modelling and Design Optimization of Large Floating Wind Turbines	Opt, Con	floating wind turbines
Carmen Kooij, 2021 (TU Delft)	Towards unmanned cargo ships: A task based design process to identify economically viable low and unmanned ship concepts	Sys	autonomous ships
Aleksandr Kondratenko, 2022 (Aalto)	Goal-based optimization in Arctic offshore support vessel design and fleet composition	Opt	arctic
Marjo Keiramo, 2021 (Aalto)	Pathways of the creative journey – the significance of a cruise ship concept design		UX design
Samantha Taylordean, 2021 (Michigan)	A Novel Framework Utilizing Bayesian Networks Structured as Logical Syllogisms to Determine Sufficiency of Early Stage Ship Design Knowledge Queries	Set	design methodology
Mark Allen Parsons, 2021 (Virginia)	Network-Based Naval Ship Distributed System Design and Mission Effectiveness using Dynamic Architecture Flow Optimization	Opt	distributed system design
Ali Ebrahimi, 2021 (NTNU)	Handling Ship Design Complexity to Enhance Competitiveness in Ship Design	Sys	design process management
Hao Yuan, 2021 (Michigan)	Early-Stage Ship Design Operational Considerations as a Thin Abstraction Enabled by a Grid-Supported Markov Decision Process Directional Decision Ensemble Framework	Set	simulation of operations
Muhammad Hary Mukti, 2022 (UCL)	A Network-Based Design Synthesis of Distributed Ship Services Systems for a Non Nuclear Powered Submarine in Early Stage Design	Set, Con, Opt	distributed systems design

Many of the listed PhD theses are related to optimization – often with the addition of accounting for uncertainty – and simulation. So far, we see surprisingly few theses on design method tackling sustainability as well as extended system boundaries, that is fleet and infrastructure design.

EMERGENT DEVELOPMENTS IN DESIGN METHODOLOGY

In many situations, the questions are just as interesting as the answers. For a state-of-the-art paper, this means asking what will be next in design methodology. Thus, in this "emergent developments" section we will include recent contributions that we either consider promising, or have received a certain degree of attention, but for which it remains to be seen whether it will have a lasting and substantial influence on the design methodology within our domain. One obvious candidate in this category is digital twin technologies, with relevant opportunities for the design of complex systems, but with tangible results still awaiting. Another is an extended system perspective by many seen as necessary for solving complex problems like sustainability and seaborne transport emission footprint. A third is the potential impact of artificial intelligence (AI) and machine learning (ML) on design methodology.

Digital twins and the influence of digital technologies on design methodology

A digital twin (DT) can be defined as a model capable of rendering the state and behaviour of a unique real asset in (close to) real time, Erikstad (2017). Inherent in the concept of a "twin" lies the concurrent existence of both a physical and a digital realization of the object. Thus, from a design perspective the DT might be deemed irrelevant simply because design is about developing *descriptions* of artifacts that typically pre-dates their physical counterpart by time gaps far from "real time". Still, DTs are likely to have an impact on (marine systems) design along three main paths:

By developing the DT during the design process:
The digital models that are central in most of today's design processes will (hopefully) eventually result in a newbuilding. Thus, by easing the "real time" requirement of the definition, the DT concept may add value to the digital design model beyond its immediate use in the design process itself. Additional defining characteristics of a DT are identity, representation, state and behaviour (Erikstad 2017). These can be entrenched into the digital model throughout the design (and production) process (Fernades and Cosma 2020), to be "born" as the digital twin counterpart to the ship at delivery, and subsequently by digital entanglement serve the vessel throughout the lifecycle.

By "designing" the DT towards digital services as a primary design objective:
It is expected by many that digital services based on DT technology will comprise an increasingly large share of the total value of a newbuilding delivery in the future (Garcia Agis et al. 2022, Drazen et al. 2019). These digital services neither will nor should come into existence as a mere biproduct of the design of the physical vessel. Rather, they should be derived from the needs and expectations of key stakeholders, and they should be designed following, in principle, the same engineering design process as for the vessel itself, as described in "Designing ship digital services" by Erikstad (2019). This includes the following elements:

- The overall goal of the service, i.e. what are the high-level operational decisions the service will support
- The primary users of the service, as well as other involved stakeholders
- The scope of the service, both from a temporal perspective as well as decision-making level
- The quality of the service, which is primarily a cost-value trade-off

The specification of "form" should follow functions and needs as in other engineering design processes. For a DT typical "form" elements are sensors type, position, quality and frequency, ship onboard digital infrastructure, capabilities for data acquisition from the vessel's "operating theatre", to name a few. We believe that it is fair to say that of the 3000-5000 sensors typically installed on a PSV, not many of those are designed into the solution from a holistic "needs perspective".

By exploiting operational experience data from DT "siblings":
During the lifetime of the vessel, the DT will continuously capture and store data from real operations based directly on sensor observations, and indirectly from the processing of these data to capture more complex vessel performance data. Naturally, the DT for a particular vessel will be "born" too late for exploiting this data stream into the vessel's own design process. Still, DT data from other vessels that are sufficiently similar ("siblings") can and will be increasingly used as an intrinsic part of future design processes.

As illustrated in Figure 11, the data from the DT can be used in the design process on different aggregation levels. On the operational level, DT data can be used to feed into vessel performance models, such as resistance and powering, motion, structural loads etc. On the tactical level, DT data can be aggregated over shorter time periods to derive for instance distributions of operational states, routing, and capacity utilization. This may provide a much better understanding of the real operational profiles that can be expected for a new design, thus feeding into the "requirements elucidation" process in terms of a reality check that often comes to the surprise of the ship owner as well. One example of this was a new trawler design by Ulstein in 2020, where they had a major revision of the design requirements based on extensive data analysis of current trawler operations. On the strategic level, DT data can be aggregated for longer time periods, up to the lifetime of the vessel.

In addition to the DT data aggregation levels described above, the temporal aspects of DT data are also important from a design perspective. In operation, the DT is typically implemented as a "digital shadow" that trails the real vessel preferably with a small latency and use sensors for observing behaviour. In design, hindsight data from DT "siblings" is also relevant as experience-based input to the process, though even more so the opportunities from "foresight" by establishing the DT at an early stage to be used for simulating vessel operations to explore and validate design solutions.

Figure 11: Aggregation levels and temporal aspects of DT data used in design (Erikstad, 2019)

DTs are still in many ways immature, and their use as an intrinsic part of the design process still need research. There are many ongoing developments where we can expect to see interesting developments towards the next IMDC. Examples are a common, open, cohesive DT model for a ship (Fonseca and Gaspar 2021), open implementation frameworks (Hatledal et al. 2020), the conversion of DT data streams into useful design input (Bekker et al. 2019) and the integration of DT and SE models for design (Arrichiello and Gualeni 2020).

The wider system perspective: Integrating vessel and fleet design, operations and infrastructure

A general insight that has emerged more clearly in the wake of the current development towards low and zero emission shipping is that the ambitions set by the IMO 2050 targets cannot be achieved only by re-designing the individual themselves. We will need comprehensive, system-wide solutions that will include the design of fleets of heterogenous vessels, the re-design of their operations, as well as the development of new commercial, legal and technical infrastructures, or what was called "the extension of system boundaries" by Hagen and Grimstad (2010). Accordingly, *systems design* is likely to take a more prominent role in the coming years.

A systems perspective may result in core functionalities that is typically integrated into a single vessel, to be distributed across several vessels of a fleet. One example is the "vessel train" concept (Colling and Hekkenberg 2020) where a fully manned lead vessel takes over navigational and situational awareness responsibilities from follower vessels as part of a waterborne platoon. Another example is the proposal for a power replenishment and emergency response vessel from Ulstein (2022), offloading core functional capacities from the cruise vessels it is intended to serve.

Extending system boundaries avoids the sub-optimization of parts of the system, thus finding better and more cost efficient overall solutions. The main challenge to take this approach into real-life design processes is the distribution of part system ownership among a large and heterogenous stakeholder group, as well as established system requirements based on domain traditions that have seldom been challenged. Take optimal speed as one example, which is a decision on the interface of the design of the ship and designing the operations, see Psaraftis and Kontovas (2014). Another example that illustrates this was the design of arctic LNG transport with a large fleet of double-acting tankers (Erikstad and Ehlers 2014). Here, a significant reduction in fleet cost to be obtained by relatively moderate redesign of the "operating context" of the fleet, such as contracts that allowed for seasonal variations in destinations and volumes, storage capacity in export ports, and re-scheduling of revision stops at the LNG production facility.

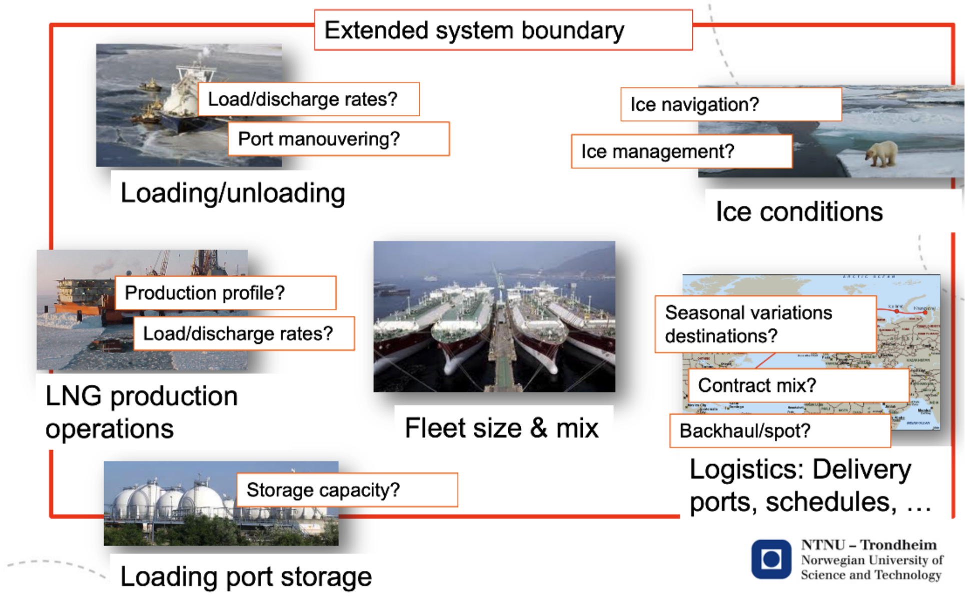

Figure 12: Extending system boundaries for LNG fleet design (Erikstad & Ehlers 2014)

Inhibitors to innovations in the maritime domain have been strong domain traditions and a bias towards standard tonnage for maintaining second-hand value. The rapidly changing context in which ships operates, and the need for new solutions to meet the emission reduction targets towards 2050 is likely to change this. As described in (Rex, 2022): "*The introduction of green corridors presents new dynamics for value creation in the shipping industry. Long-term contracts with not only cargo owners but also fuel producers will allow long-term fleet efficiency optimisation at the expense of access to the asset game. This is a shift that will champion cash flow stability, economies of scale, standardisation and lower cost of capital. It remains to be seen if new business models will begin to redefine the competitive landscape*" (Rex, 2022).

Towards the next IMDC, we expect this systems perspective to take a more central position in the design of tomorrow´s solutions, and with the associated development of new and extended design methods to cater for this.

AI, ML and KBS: Still hyped, or for real this time?

"Hype cycles" are a common phenomenon across industries and technology areas, where an initial wave of inflated expectations is followed by a trough of disillusionment, and, in some cases, a renewed start based on a more mature platform to achieve widespread adoption. Those that have followed developments in design methodology for more than a few decades will remember the high expectations towards artificial intelligence (AI), expert systems and knowledge-based systems (KBS) in the 80s and 90s. For the design community as such, the contribution from Coyne et al (1990) in their book "Knowledge-based design systems" was important. There were also several significant contributions specifically for ship design, such as Hees et al. (1992) with their QUASTOR KBS tool for preliminary design, and MacCallum & Duffy (1987) at the University of Strathclyde developing expert systems for the early design stages.

Still, it is fair to say that the expectations from many at that time for AI-related technologies to become a major factor in real-life design processes by the end of the millennium did not come through, and the research interest in this field diminished. As an illustration, none of the papers presented at the 2009 IMDC in Trondheim were related to this topic area.

During the last decade we have seen an increased focus on AI-related technologies, with efficient, real-life implementations for a wide spectrum of applications. This has ranged from photo recognition and natural language processing on mobile phones, to tackling complex problems on an unprecedented level such as chess with Google's AlphaZero, (Silver et al, 2018). There has also been a shift in the underlying technology focus, from predominantly expert systems based on logically stringent reasoning over rules structures, towards neural network models and data mining/machine learning. This has changed the way knowledge is embedded into the system, from human experts entering facts and rules in expert systems, to self-learning algorithms and reinforcement learning in neural networks. As an example, AlphaZero reached its "superhuman" performance in chess by using a generic AI platform, defining legal moves and then start playing an extremely large number og games between two virtual players. This was combined with reinforcement learning based on the single outcome of winning or not. No domain knowledge, such as human evaluations of different intermediate positions etc. were needed. How this capability will project from this very complex, still well-defined and structured, domain into other, less structured domains, remains to be seen.

One such complex, less structured domain would be engineering design in general and design methodology in particular. In a recent special issue of the Journal of Mechanical Design (Allison et al. 2022), three research interfaces between engineering design and AI were identified: The integration of AI methods directly into engineering design methods, the creation of new AI capabilities that are inspired by engineering design, and the development of engineering design methods for systems in which AI have a dominant role, such as in autonomous vessels. Recent examples are the use of AI for the prediction of ship operational parameters (Alexiou et al. 2021) or power prediction using neural networks (Parkes et al. 2018).

CONCLUDING REMARKS

In this paper we have summarized the state-of-the-art in marine systems design methodology. We first introduced some high-level trends in overall design strategy, notifying that most contributions within this topic area will be a combination of these. Further, we highlighted some more specific developments, such as design-for-sustainability, design for flexibility and uncertainty, design-for-safety, simulation-based design and WASP. Finally, we pointed towards what we believe will be emerging focal topics for the years to come.

As we noted initially, a SoA paper will naturally be a snapshot from the subjective perspective of the authors. There will be many contributions both from industry and academia that we have not included, and it is likely that other authors would have made a different selection.

Still, we hope we have been able to paint an overall picture that is exciting from a design methodology point-of-view. More than before there seems to be a consensus within the maritime industry that radically new, system-level solutions need to be developed to tackle some of the major challenges we see today related to global warming, energy distribution and global logistics chains, to name a few. To meet these challenges, new and improved design methods must be developed and implemented into practical use in industry. The next IMDC will be a checkpoint to see if we have been able to take the required steps in the right directions.

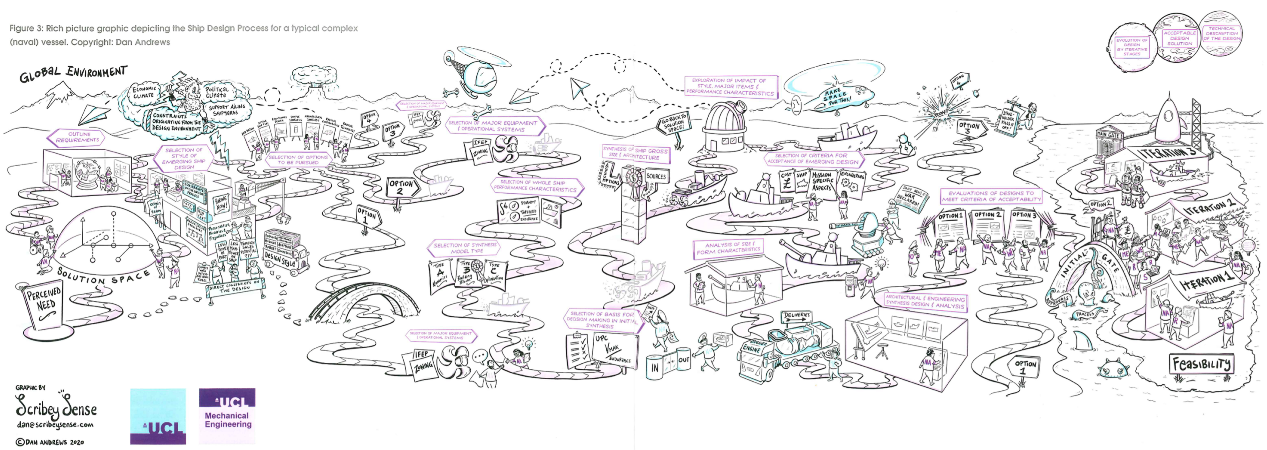

Figure 13: The complexity of the ship design process pictured by Dan Andrews (Andrews 2021)

To conclude this SoA paper we have chosen to include the illustration of the ship design process by Dan Andrews in Figure 13. This captures the “wickedness” of design, and the complexity of the task. At the same time it reminds us of what one of the founding fathers of IMDC, Stian Erichsen, used to say: “One of the most important jobs for an engineer is to make complex things simple”.

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