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THE DESIGN KNOWLEDGE MANAGEMENT SQUARE - A FRAMEWORK FOR EARLY STAGE COMPLEX SHIP DESIGN

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Abstract. This paper presents and demonstrates a new design thinking framework for early stage complex ship design, called the Design Knowledge Management Square (DKMS) framework. The DKMS framework provides a structure that explicitly incorporates the collaborative nature of complex ship design, contrary to other models or frameworks that primarily focus on the technical integration of tools and methods to describe early stage complex ship design. The DKMS framework is applied to three case studies: 1) multi-disciplinary early stage design of complex ships, 2) the integration of concept design generation and analysis methods, and 3) the application of design rationale to support collaborative design decision-making. The case studies show that the DKMS framework provides added value by explicitly describing both the collaborative and technical nature of complex ship design. Thereby the framework helps to analyse, support, and understand complex ship design.

Keywords: Design framework, Complex ship design, Early.

1. Introduction

This paper presents and demonstrates a new design framework for early stage complex ship design, called the Design Knowledge Management Square (DKMS) framework. The DKMS framework provides a structure that explicitly incorporates the collaborative nature of complex ship design and describes the interrelationship between collaborative and independent problem solving, and therefore adds to other models or frameworks that primarily focus on the technical integration of tools and methods to describe early stage complex ship design.

1.1. Research motivation

The work presented in this paper is motivated by the following observations:

1. Individual research focused at the development of design methods applicable for early stage complex ship design might lack a direct contribution to higher level research problems. That is, the developed methods might need to be scaled up to be practically applicable, or might rely on other methods for input. For examples see Section 3.2. of this paper. Translating insights obtained from the individual methods to higher level problems is not trivial, as it requires considerable experience with the higher level problem. Yet, translating such insights to higher level problems would 1) be beneficial for collaborative design and 2) increase the yield of the individual bits of research as it is believed that the combination of the individual researches would enable the designer to explore a larger part of the higher level problem, than finding just the mere sum of the individual researches.

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2. In contrast, collaborative work on the integration of design methods resulted in more capable tools and methods, but also to the identification of direct insights into solutions for higher level research problem. Even if tools were not actually integrated from a software point of view, design processes and gaps between tools were identified (e.g. Habben Jansen et al. (2019)). Similar benefits could be realised in practical ship design. Indeed, if an engineer is not able to convey potential issues between conflicting design aspects related to the work of other engineers, these aspects might not be sufficiently solved. Hence, communication skills are key (Andrews, 2018b).

3. Because of the inherent decomposition of problems in research and design, and the identified benefits of translating insights obtained from solving decomposed sub-problems into recomposed problems, the communication of design research and design work in the context of decomposition and recom-position of complex ship design problems becomes essential.

These considerations motivated the development of a new design framework, called the Design Knowledge Management Square framework.

1.2. Problem background

Generally, ships can be divided into two classes (van Oers, 2011): transport vessels (e.g. container ships and bulk carriers) and service vessels (e.g. crane vessels and frigates). While transport vessels transport goods across the globe, service vessels perform missions at sea. Compared to transport vessels, service vessels are typically complex products, for three reasons:

1. The complexity of the ship itself, e.g. due to the large number of systems and the interrelationships between these systems (Simon, 1969). These systems are required to perform required missions.

2. The evaluation of the performance of these vessels (Andrews, 1998). For instance, how to measure the effectiveness of a frigate operating in peace-time operations?

3. The formulation of the actual design problem, i.e. the right set of requirements, is the main challenge during early stage design. Therefore, early stage complex ship design has been characterised as a ‘wicked problem’ (Andrews, 2018a). As Rittel and Webber (1973) state, “setting up and constraining the solution space and constructing the measure of performance is the wicked part of the problem. Very likely it is more essential than the remaining steps of searching for a solution which is optimal relative to the measure of performance and the constraint system.”

Roberts (2000) describes three types of problems, namely simple, complex, and wicked problems. These types of problems differentiate with regards to consensus between actors. In simple problems, actors have consensus on the problem and the solution. In complex problems, the actors have consensus on what the problem is, but don’t agree on the solution to that problem. In wicked problems, actors lack consensus on both the problem and solution.

Therefore, by definition, a wicked problem implies decision-making involving multiple actors. These actors might have conflicting perceptions of the problem, and thus might prefer different solutions. Proposed solutions might compete with other actors’ preferred solutions. A practical example is the position of an ammunition store on a naval vessel. A vulnerability specialist wants this store below the waterline, a safety specialist far from accommodation, and a user close to the weapon. Also, a logistics specialist wants easy access and the naval architect considers space and weight.

Additionally, the development of solutions might change perceptions on the problem, and can lead to the identification of new interdependencies between solutions. These interdependencies might be hard to identify beforehand, for example, because design decisions for one class of ships can impact another class that is concurrently being designed. However, proper early stage concept design should reveal, at least the major, hidden implications (Andrews, 2018a).

Indeed, complex ship design involves many design disciplines and specialists working on potentially conflicting or competing design aspects, actors need to align and reach consensus. An example of conflicting design aspects is the preference to maximise the vertical position of main sensors to extend the sensors’ range, and the need for a stable ship (i.e. lower centre of gravity). Although this example could be classified

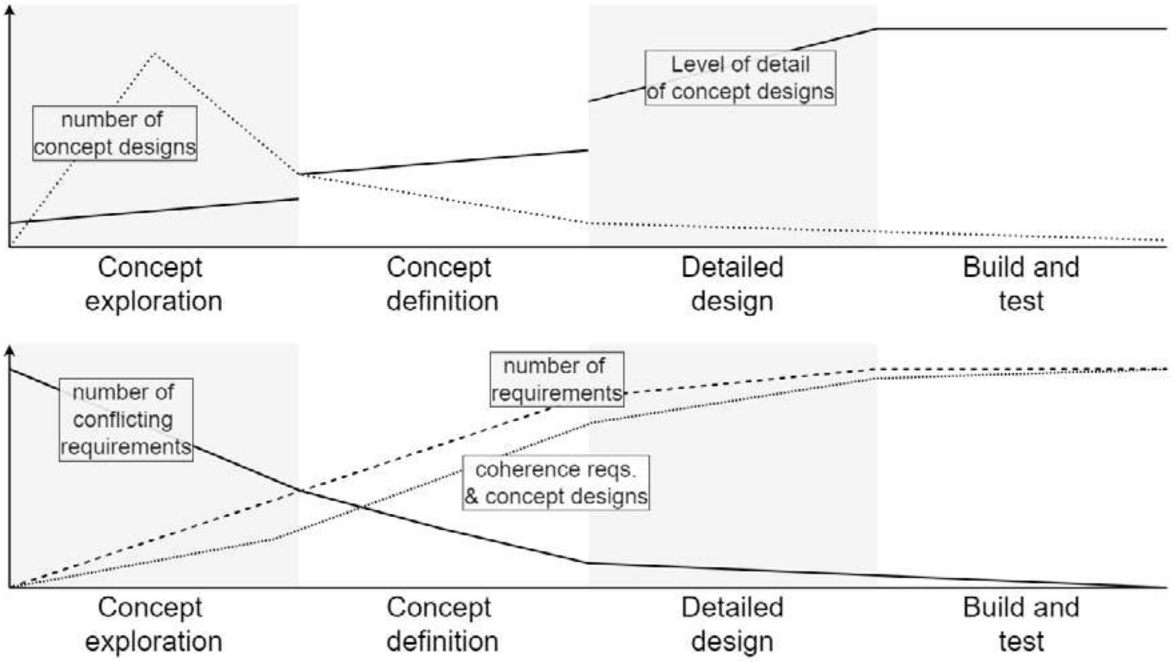


Figure 1.: Development of requirements (problem) and concept designs (solution) over a typical ship design process timeline. Top figure after (van Oers et al., 2018). The Y-axis indicate increasing values.

as a complex problem (since its rather well defined), it might also be an example for a wicked problem if multiple actors are involved and if these actors are not yet in line (e.g. because they don't understand the implications of design decisions on other design disciplines and aspects yet). Certainly in concept exploration, disconnected design efforts might take place to understand parts of the design problem, e.g. future weapon or propulsion system concepts (Van Bruinessen, 2016). Eventually a recomposition into an overall satisfying design solution is required. If individual design efforts are not constrained by overall design solution implications (e.g. costs, or conflicts with other design aspects), the congregated set of design solutions can be over-budget and over-ambitious. To explore the problem and solution spaces, with respect of need and affordability, is the typical goal for early stage design efforts. To develop a mutually satisfying concept design, conflicting and competing design aspects need to be resolved (Wolff, 2000; Roberts, 2000; Habben Jansen, 2020), for instance via a stakeholder dialogue (van Oers et al., 2018).

The development of concept designs to inform the stakeholder dialogue on the technical and financial implications and risk (e.g. with regards to project duration) of requirements is considered essential to guide the formulation of the design problem (i.e. requirements) (Andrews, 2018a; van Oers et al., 2018; Duchateau, 2016). Initially, these requirements can be overambitious, conflicting, and ill-defined (Andrews, 1998). As Shields et al. (2016) state: "design is the simultaneous exploration and definition of an engineering problem", a process called 'requirements elucidation' (Andrews, 2018a). Later design stages are more characterised by an engineering process - although that fact does not exclude social design aspects, such as creativity (Snider et al., 2016). This means that earlier design efforts are mainly aimed at understanding the design problem, while later design efforts prepare the concept design for the eventual building of the ship. Figure 1. represents a general ship design process timeline. It shows the nature of early stage design by a diverging number of concept designs, a reduction in number of conflicting requirements, and a relatively limited level of detail of concept designs. During later stage design, the level of detail is high, but only few concept designs are developed, while the coherence between requirements and the concept designs is increasingly high. Eventually, the ship is built and compliance with the requirements is evaluated during system testing and sea trials. However, this seems to conflict with the nature of wicked problems.

Indeed, Rittel and Webber (1973) explain that wicked problems have, among others, the following characteristics:

1. ‘There is no definitive formulation of a wicked problem’. To solve a problem, one needs to understand it. However, in wicked problems, a further understanding of the problem leads to new questions, and thus to a widening of the problem statement. To completely understand a wicked problem, the full range of conceivable solutions needs to be known beforehand – which is simply not possible.

2. ‘Wicked problems have no stopping rule’. Because the process of understanding the problem coincides with the process of solving the problem, additional efforts to solve the problem might lead to a better solution. Therefore, in practice problem solving is terminated due to external factors, such as available time or budget, not because the problem is fully defined, i.e. solved.

In contrast to these general characteristics of wicked problems, the complex ship design problem seems to be resolvable. Indeed, eventually a ship can satisfy both a coherent set of requirements *and* the client. In terms of the three types of problems described by Roberts (2000), complex ship design seems to transition from a wicked problem (during concept exploration and early concept definition) to a complex problem (later concept definition and detailed design) and a simple problem (build and test). Under the assumption that all actors want to have a satisfying ship (from their perspective), it seems to be a reasonable assumption that ‘wickedness’ reduces during the complex ship design process. This does not imply that the initial design efforts can lead to simple solutions. Indeed, real technical and engineering challenges remain later in the process, but not necessarily from a requirements, problem-setting perspective.

As identified above, consensus is an essential factor in solving wicked problems. Since consensus is directly connected to the actors involved in decision-making, the social aspects of decision-making need to be considered to no less extent than the technical aspects. Consensus can be built when knowledge of the problem is negotiated, understood, and acknowledged across actors. Negotiation is dependent on the following three main factors: negotiators’ interests and priorities, strategies and social interactions, and outcomes (Brett and Thompson, 2016). The observation that consensus is essential in multi-actor decision-making motivated the definition of the DKMS framework in terms of negotiated knowledge between actors involved in complex ship design, i.e. an established negotiated basis of correctness of information to allow for interaction between actors with different perspectives on that information (De Bruijn and Ten Heuvelhof, 2008, p70).

1.3. Existing models describing early stage ship design

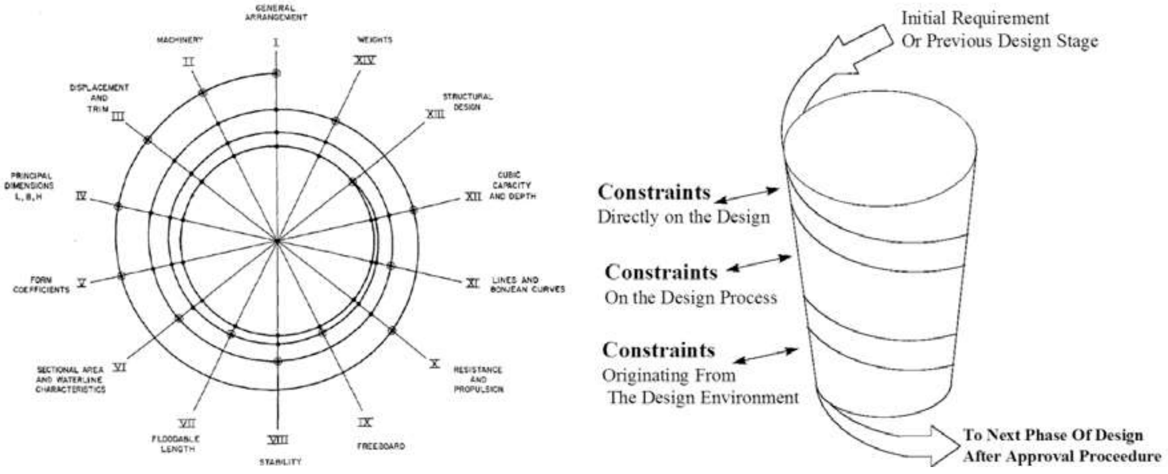
Before establishing the need for a framework applicable to the nature of complex ship design, as described above, a range of existing models describing early stage ship design is investigated. Each model is shortly described, and analysed with respect to its description of the technical and social aspects of complex ship design.

1.3.1.Evans (1959) and Andrews (1981): ship design spiral

Evans (1959)’s ship design spiral is typically referred to as representing traditional point-based design. It stresses the iterative nature of ship design, as shown in Figure 2.a. The iterative nature of ship design comprises many closely interrelated design aspects. As an example, a ship’s stability, hull from, resistance, propulsion plant, and fuel capacity are all related. Changing one aspect can imply the reconsideration of all aspects. The main emphasis of the ship design spiral lies on the fact that many design issues can be considered in sequence until a single sufficiently balanced design is obtained (Singer et al., 2009). The method is mainly suitable for variant design, where an existing design is taken as a starting point of the design process. However, complex ships are typically one-off or low-production run designs, which can only marginally rely on earlier designs.

Andrews (1981) extended the 2D design spiral into a 3D representation, see Figure 2.b. This model emphasises the interactions within the design process, while external constraints are imposed on the design. The following constraints are defined (Pawling et al., 2017):

1. Constraints directly on the design, i.e. direct impositions from, for instance, customers, users, specialists, and classification societies.



(a) 2D ship design spiral (Evans, 1959)

(b) 3D ship design spiral (Andrews, 1981)

Figure 2.: 2D and 3D ship design spirals

2. Constraints on the design process, e.g. available data and design tools, which might be influenced by the design team.

3. Constraints originating from the design environment, e.g. the education of designers, legislation, and major organisational changes. The design team has no influence over these significant constraints.

This way, the 3D spiral underlines that considerable dialogue takes place between the designer and other stakeholders both inside and outside the iterative design process (Pawling et al., 2017). Criticism on the design spiral is that it does not describe the non-linearity which is typical for the complex ship design process (Brown, 1986; Pawling et al., 2017). For example, referring to Figure 2.a, if stability cannot be satisfied for already selected principal dimensions and general arrangement, one is likely to reconsider these earlier chosen parameters, instead of completing the current spiral.

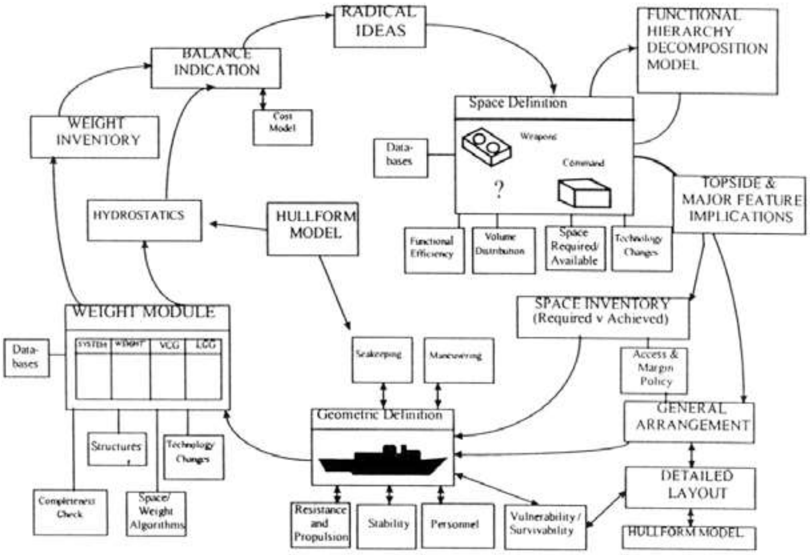


Figure 3.: Building block design methodology (Andrews and Dicks, 1997)

1.3.2. Andrews and Dicks (1997): building block design methodology

To include more of the non-linearity of complex ship design Andrews and Dicks (1997) proposed an interactive design approach, depicted in Figure 3. The methodology allowed tools to inform the designer on design balance, and let the designer decide how to adopt the design to achieve balance. The methodology allows the designer to follow various paths in the design process. This model emphasises the role of the designer, which is also further advocated in Andrews (2018b). Two drawbacks are, however, that it does not explicitly contain the external constraints present in the 3D design spiral, and that it is tailored to ‘the designer’, while most ship design efforts (even in the earliest stages) are undertaken by multiple actors, see Section 1.2.

1.3.3. Wolff (2000): perfect design

Wolff (2000) investigated how the idea of ‘perfect design’ could be applied to improve individual and group decision-making in naval ship design. Perfect design is a derivative from the perfect competition model in economics (Knight, 1921). Perfect design relies on a number of prerequisites, grouped in three categories (Wolff, 2000):

Table 1.: Requirements for group decision making processes (Wolff, 2000, p115)

	1st phase: common interest	2nd phase: bargaining
Type of difference of opinions to be dealt with are:	real basic value judgments, alleged facts, logical analysis	conflicting personal or sectional interests
Means of settling differences of opinions are:	demonstrations, ethical persuasion, logical discussion	political compromise reached by, if necessary, offering compensation
Differences of opinion and Arrow’s voting paradox are settled under the umbrella of:	sequence, dominance, invariance	Scitovsky’s compensation criteria
Requirements for decision-makers are:	should not represent stakeholders, should not be budgetary responsible	should represent stakeholders held budgetary responsible, possess means of compensation

1. Perfect behaviour of actors, enabled through perfect knowledge, complete rationality, and complete honesty and openness.
2. Perfect adaptability, through instantaneous availability and continuous variability of information, design tools, software and specialists, but also of the warship and parts of the warship such as equipment and crew members;
3. Perfect freedom of actors, such that they can individually act accordingly to their motives in design, procurement and use of the warship.

Under perfect design no recursive design work needs to be performed. In practice, recursion is frequently required because of 1) wrong assumptions (i.e. less than perfect knowledge) and 2) not recognised relationships between pieces of information (i.e. less than perfect availability of knowledge). Proposed solutions to these issues are decoupling the design (i.e. decomposition), and managing recursion effectively by using an information structure.

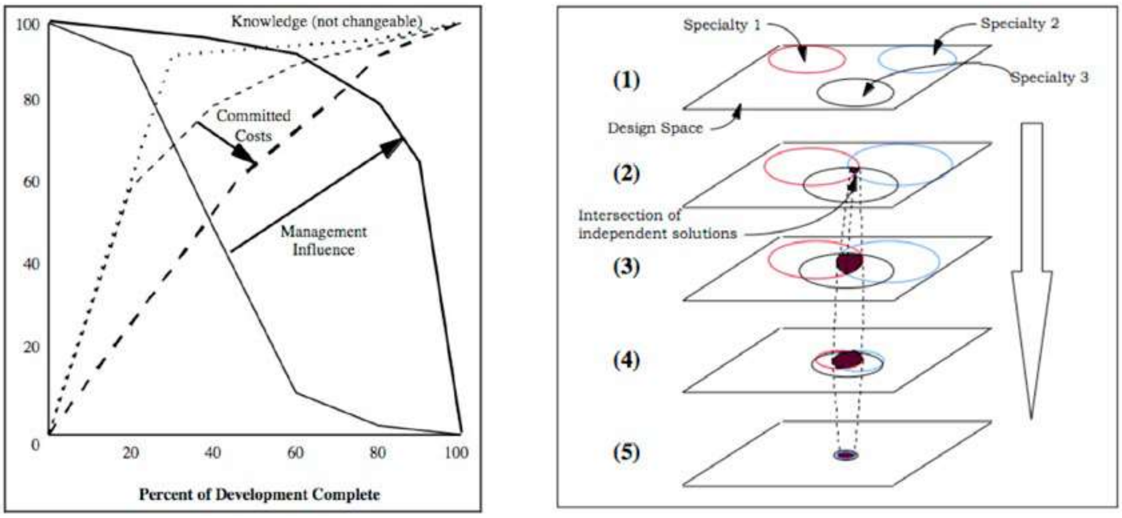
To ensure the ideal conditions described by perfect design, the elements knowledge, adaptability, and decision-making are important. Wolff (2000) argues that the quality of the decision-making process can be improved by increasing the rationality of decision-makers’ behaviour. Based on the characteristics of individual and group decision-making, a set of requirements for a two-phase group decision-making process for early stage ship design was proposed, presented in Table 1. First, this process aims to arrive at a design where common interest is satisfied. Second, remaining conflicts are solved via bargaining between actors to find mutual agreed compromises.

The efforts of Wolff (2000) to improve decision-making in complex ship design contribute to the understanding of the nature of collaborative design decision-making in complex ship design. However, it lacks the focus on the technical complexity of warship design, which is also an important factor in early stage complex ship design.

1.3.4. Singer et al (2009): Set-Based Design

Set-Based Design (SBD) aims to delay critical decisions to the latest point possible. This is important, because the important decisions are taken early in the design process, typically with incomplete or incorrect information. By delaying decisions, SBD enables design disciplines to elaborate on the understanding of the feasible design space from their perspective. This enables a reduction of early committed costs, and an increase in time available to stakeholders to influence the design (Singer et al., 2009). This is visualised in Figure 4.a. The optimal and feasible design is found by intersecting the various design spaces, as visualised in Figure 4.b.

In SBD, the independent exploration of the design space by each design discipline is advocated to avoid the “problematic” iterative paths in point-based design (Bernstein, 1998). However, Section 1.2. explained that the dialogue between stakeholders is key to achieve alignment and consensus on the overall problem. This process of alignment, in contrast to Figure 4.a, does increase the problem knowledge across design teams. Therefore, it seems that SBD is primarily focused on generating designs (i.e. solutions) in a better way while improving the understanding of individual parts (e.g. discipline-based) of the overall design problem before critical decisions are taken, but less on the definition of the overall design problem itself. Indeed, SBD is expected to be of most value when most of the requirements have been set, i.e. between the Analysis of Alternatives and Preliminary Design phases (Singer et al., 2009).



(a) Impact of SBD on the design process (Bernstein, 1998) (b) SBD process (Bernstein, 1998)

Figure 4.: Set-Based Design

1.3.5. Shields et al (2016): ship design as a complex system

Shields et al. (2016) explain the complexity of naval ship design through the analogy of landscapes. The role of the designer is to find the optimum design, i.e. the highest point in the landscape. For complex ships, such as naval ships, this landscape changes over time. As a consequence, an optimal solution in the current state might be an inferior design at a later stage. Three types of factors result the complex ship design landscape to ‘dance’:

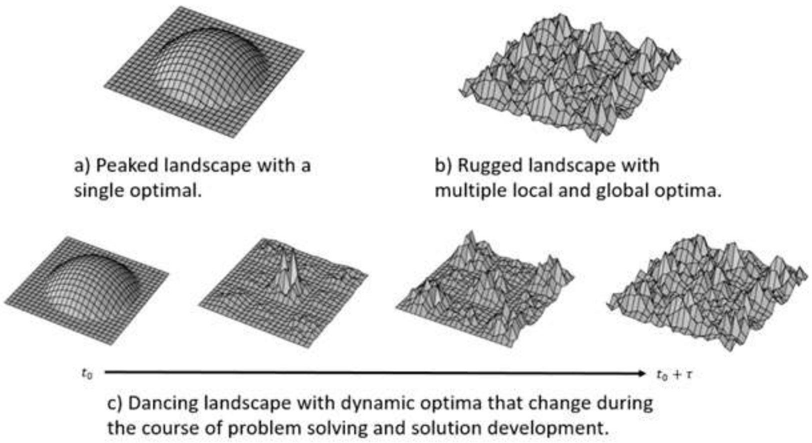
1. Endogenous, i.e. changes in the landscape due to factors internal to the problem. The current design solution might become unfeasible when previously unknown interdependencies or problems are identified after a decision has been taken. For example, refinement of weight assumptions of a radar system can reveal stability issues for the overall vessel.

2. Exogenous, i.e. changes in the landscape due to factors external to the problem, such as changing budgetary constraints or mission requirements.

3. Temporal, i.e. changes in the landscape due to path-dependent interactions of exogenous and endogenous factors. For example, the success of zero emission ships is highly dependent on the development of green fuel propulsion technologies.

They advocate the use of design tools and processes to primarily generate knowledge for decision-making through time. Examples of methods aimed at reducing the complexity of design are Set-Based Design (Singer et al., 2009) and Systems Engineering (Haskins et al., 2006), which respectively delay design decisions till uncertainty is resolved, and provide a rigorous description of the design process (Shields et al., 2016). In addition, Shields (2017) developed a Knowledge-Action-Decision (K-A-D) framework that "describes the changing relationships between the ideas, concepts, and evidence designers use to progress a design activity. Analysis of the K-A-D Framework through a network representation allows the importance of knowledge structure elements to be measured, the trajectory of a design activity to be identified, and opportunities to prevent design failures to be found".

Although the dancing landscape analogy for complex ship design is powerful, the identified factors seem to focus on the technical challenges of design, although the interdependencies with stakeholders are also acknowledged Shields et al. (2016).


a) Peaked landscape with a single optimal.

b) Rugged landscape with multiple local and global optima.

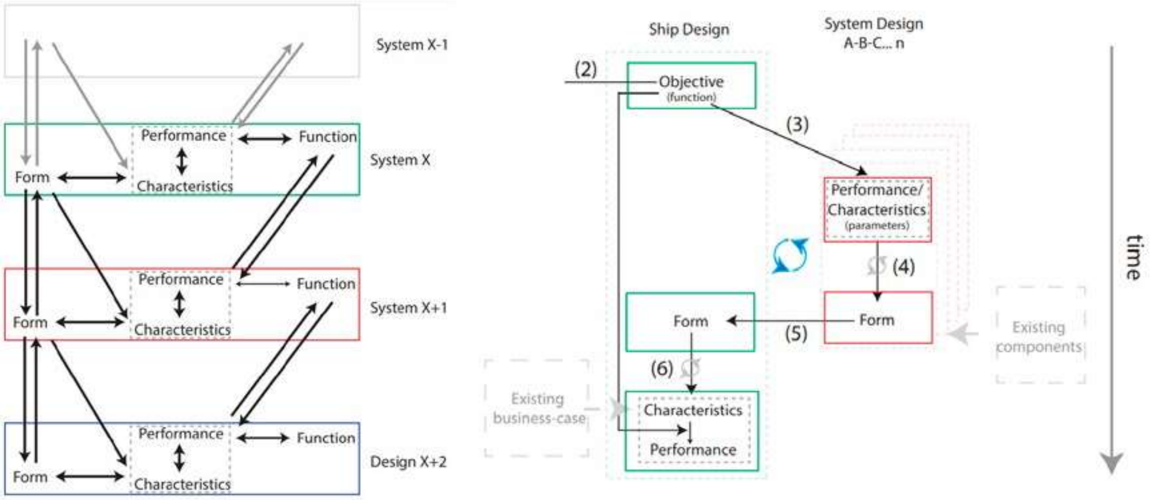
c) Dancing landscape with dynamic optima that change during the course of problem solving and solution development.

Figure 5.: Classes of design problem landscapes. Each point on the landscape represents a solution concept and the point's height represents its fitness based on the designer's problem understanding (Shields et al., 2016).

1.3.6. Van Bruinessen (2016): CK theory

Van Bruinessen (2016) used CK (Concept-Knowledge) theory to analyse co-evolving innovative ship design. CK theory comprises a Concept space (where propositions, such as ideas, are still undetermined) and a Knowledge space (where propositions are either true or false). Based on this analysis, a model for cohesive co-evolvement of systems-of-systems and a design process for co-evolving ship and system design were proposed, see Figures 6.a and 6.b.

Van Bruinessen (2016) focused on the technical content of the interaction between actors working on individual system or ship design, but identified that the social interaction between actors appears to be important as well. Indeed, "[...] the role of this social dimension became more evident, as the explicit design



(a) A model of cohesion (Van Bruinessen, 2016)

(b) A design strategy, based on the interaction between system and ship design (Van Bruinessen, 2016)

Figure 6.: Modelling innovative design (Van Bruinessen, 2016)

strategy required different actors to think and discuss their role within the project" (Van Bruinessen, 2016). The use of such explicit design process leads to the situation where the technical and social interactions become the basis for design (Van Bruinessen, 2016, p84). This underlines the outline of early stage complex ship design in Section 1.2.

1.4. Need for a new design framework for early stage complex ship design

All investigated models describe or acknowledge, in varying degree, the complex nature of complex ship design. However, none of the investigated models explicitly describes both the technical and social side of complex ship design, or explains how the understanding of the design problem enhances in multi-actor decision-making. Some focus primarily on the technical side (Evans, 1959; Andrews, 1981; Andrews and Dicks, 1997), other focus primarily on the social side (Wolff, 2000) or acknowledge it (Van Bruinessen, 2016; Singer et al., 2009; Shields et al., 2016). Yet, such understanding is essential to fully comprehend the nature of complex ship design, as elaborated in Section 1.2.

Hence, there is a need for a design framework that comprises the (intertwined) technical *and* social aspects of multi-actor collaborative (design) efforts in complex ship design. The application of such design framework is expected to benefit complex ship design as it stimulates the creation of negotiated knowledge, which is ultimately the basis for multi-actor decision-making. In addition, the DKMS framework can be used to describe, understand, analyse, and support complex ship design problems and solutions in techno-social terms.

2. The Design Knowledge Management Square framework

In this section, the Design Knowledge Management Square (DKMS) framework is elaborated on. First, the main DKMS framework elements are presented. Then, the relations between the main DKMS framework elements are introduced.

2.1. DKMS framework elements

This Section elaborates on the main DKMS framework elements. In addition, brief notes on the transitions between the elements will be provided, i.e. how the main elements fit together. Section 2.2. will provide more details on the transitions.

The DKMS framework comprises four main elements:

1. Specific Problem
2. Specific Solution
3. Generalised Problem
4. Generalised Solution

The terms 'Specific' and 'Generalised' relate to different levels at which the problem and solution are defined and addressed. Figure 7. shows a visualisation of the DKMS framework. The four main elements are further detailed below.

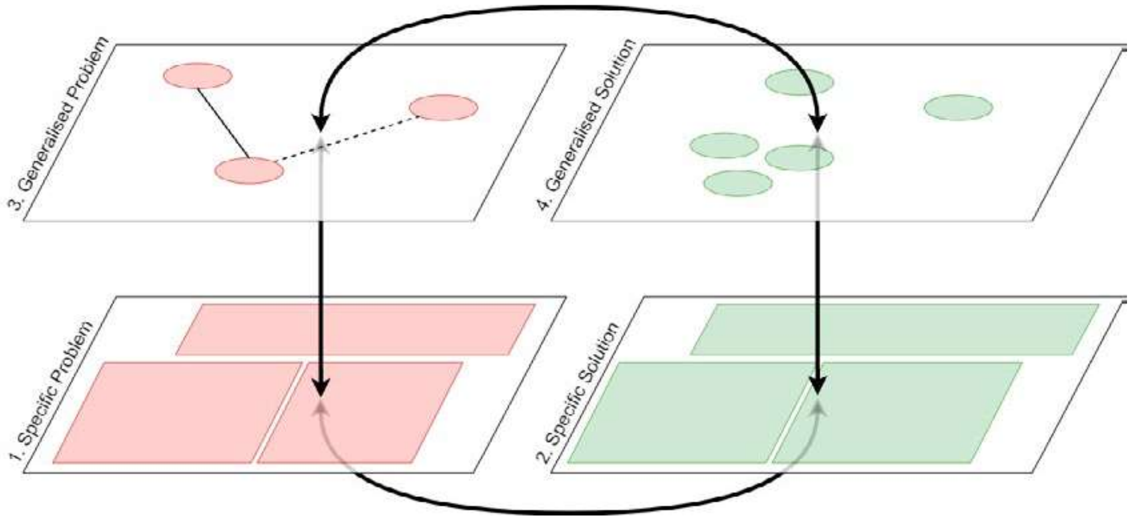


Figure 7.: Visualisation of the DKMS framework, showing the four main elements and transitions between the elements.

2.1.1. Specific Problem

A Specific Problem (SP) is a problem that impacts a specific actor. An actor might be an individual designer or specialist, but may also comprise multiple people, such as a design department or a company. As an example of the latter, actors can be a shipyard and a Navy. An SP might be a decomposed sub-problem of a larger problem (i.e. Generalised Problem, GP), or might be a specific view, or perspective, on the larger problem. Consider for example the perspectives one can take on the ship evacuation problem. One can focus on routes (i.e. pattern of people moving through a layout), or on the time it takes to evacuate. These are very related approaches, but allow for different methods to be applied.

An SP can have interrelationships with other SPs. These interrelationships might be of a technical nature, but might also be non-technical. To clarify these two types of interrelationships consider the following two examples:

- Example 1: consider three designers working on the design of a hull form, a propeller, and an engine to meet a speed requirement for a given displacement. The three design problems can be represented by three SPs that have a high technical interrelationship.
- Example 2: the problem of acquiring warships abroad (satisfying the Ministry of Foreign Affairs) or domestic (satisfying the Ministry of Economic Affairs or the Ministry of Interior and Kingdom Relations), while providing the best technical capability for the navy, represents non-technical interrelationships.

These interrelationships might be known beforehand, or might be discovered later in the process. In the case interrelationships are known, actors might neglect these, in order to generate design solutions that maximise the utility for their perspective on the design.

2.1.2. Specific Solution

The Specific Solution (SS) is the solution to a SP. Depending on the nature of the SP, the SS can be 1) a design method, 2) a (part of a) concept design, or 3) design insights, i.e. a better understanding of the SP, without fully developed solutions. In general, the efforts to arrive at an SS are either aimed at generating understanding of the SP, or at solving the SP.

The generation of an SS might lead to the identification of new interrelationships, either between SPs or SSs. A reason for the late identification of these interrelationships is incomplete information during the formulation of the SP (Wolff, 2000).

Referring to the examples above:

- The SSs to Example 1 are a specific hull form (or a set of feasible hull forms), a (set of) propeller(s), and a (set of) potential engine(s).

- The SSs to Example 2 are to acquire (parts of) the warship abroad, or to acquire (parts of) the warship from a national shipyard. Note that the acquisition process in the end should guarantee a capable vessel for the navy, although this might not be the (ultimate) goal for the ministries.

2.1.3. Generalised Problem

The Generalised Problem (GP) comprises the set of SPs, and the known interrelationships between these SPs. In essence, the GP represents a wicked problem. The set of SPs might be incomplete, since ‘there is no definitive formulation of a wicked problem’ (Rittel and Webber, 1973). Therefore, the formulation of the GP might change when actors propose new solutions to the GP or new perspectives to SPs. Alternatively, the GP can be used to describe a complex problem as a decomposition of smaller nested problems. These smaller problems could be GPs itself, but could also be the SPs that from the GP.

- The GP for Example 1 might be ‘the ship shall sail 25 knots at a displacement of 5000 tons’. There are likely multiple means to provide this capability.

- The GP for Example 2 is more complex, where the warship is a key asset for the Navy, but for the Ministries a ‘mere asset’ to satisfy (potentially conflicting) national or international relationships. The solution space and interrelationships for this GP might be significantly under-defined.

2.1.4. Generalised Solution

The Generalised Solution (GS) comprises the set of SSs, and the interrelationships between these SSs. These SSs are proposed by actors to solve the GP, from their perspective. The latter stipulation is essential. Indeed, actors might propose solutions that conflict with solutions of other actors. This might happen when an overly optimised local solution is proposed that ignores other factors. In other words, the recomposed SSs (i.e. the GS) might not be a satisfying solution to the GP for all actors. Multi-actor decision-making techniques, such as negotiation, will be required to generate synergy between actors. That is, actors are made aware of the negative impact of their preferences from the perspective of other actors. An actor might become aware of previously unknown interrelationships between SPs or SSs. The GP and GS are constructed through a dialogue between actors (i.e. the stakeholder dialogue). In this stakeholder dialogue, actors might change their perception of the GP, try to change other’s perspectives, and influence the GP and SPs such that the impact on their own SS is minimised such that their own objectives are satisfied. Through the dialogue, new interactions as well as SPs might be identified (i.e. ‘We did not think about this before’).

- In Example 1, actors might use Set-Based Design to identify mutually feasible hull forms, propellers, and engines, as a coherent GS to satisfy the GP.

- In Example 2, the preferred solutions are per definition conflicting. Hence, it is likely the Ministries will use a process of bargaining (Wolff, 2000) to (partially) decide whether a domestic or foreign shipyard will be awarded the contract.

As elaborated on in Section 1.2., the actor decomposition might change as well. This might lead to renewed perspectives on the GP or GS. For instance, a naval architect might join the three designers in Example 1 with the message that the selected engine will not fit the overall arrangement of the vessel. This can change the SPs for all actors, since the naval architect might investigate alternative arrangements to create more space for the engine room, and the mechanical engineer might search for alternative engines, aware of the new (say, height) constraint imposed by the overall ship layout.

2.2. Transiting between DKMS elements

This section elaborates on the transitions between the main DKMS framework elements. In ship design, past research has stressed the importance of considering the social, human part of design, see for instance (Van Bruinessen, 2016; Kana et al., 2016). But also outside ship design, research has found that design is not pure technical, nor is it pure social. Actually, technological and social aspects are often interwoven. For example, Piccolo et al. (2019) found that design iterations of a biomass power plant increase, amongst others, when the number of stakeholders increases *and* where design activities integrate and generate a high amount of information. Another example is Minneman (1991), who sees design to be both technical (e.g. transiting from specifications to a solution) and social. According to Minneman, the social activities (such as meetings) frame, constitute, and give meaning to design work. The technical and social aspects are intertwined, such that the social activities produce the technical results.

As shown in Section 1., also complex ship design involves, by nature, both technical and social aspects. Therefore, the transitions in the DKMS framework comprise both technical and social elements.

- **Technical aspects** relate to solving of the technical design problem at hand. Therefore, these aspects comprise, for instance, the generation of technical drawings, calculations, the decomposition of requirements etc.

- **Social aspects** relate to the actors, in two ways. On one hand, social aspects relate to actors themselves. For instance, which preferences, experience, and bias they have might dictate the way they solve the problem. On the other hand, social aspects relate to the interaction between actors. Examples are how actors behave in dialogues, how open they are to learning from others, and how they involve other actors in their decision-making due to factors such as culture, social position (e.g. client versus contractor), and innovative nature.

Each transition in the DKMS framework comprises both technical and social aspects, as indicated by examples provided in Table 2. Since design is ultimately a human task (even if calculations etc. are automated), the technical and social aspects can be intertwined. For example, the experience (i.e. social) of an actor might influence the selection of calculation methods (i.e. technical). Hence, by including both aspects, the DKMS framework can contribute to a wider understanding of the nature of complex ship design. To implement this understanding in practice, future research will need to investigate how design methods and design education can be aligned with this goal.

Table 2.: Examples of technical and social aspects of the four transitions in the DKMS framework.

	Aspects	
Transition	**Technical**	**Social**
GP to SP	Decomposition of requirements	Reasoning; assumptions
SP to SS	Drawing generation; calculations	Experience; preferences
SS to GS	Recomposition of solutions	Dialogue
GS to GP	Performance evaluation	Learning; negotiation; experience

3. Demonstrating the DKMS framework

To demonstrate how the DKMS framework might be used, this section provides three brief examples. Each example shows how the DKMS framework describes an increased understanding of the Generalised Problem over time. The first example concerns a general design case solved by multiple design teams focusing on different design aspects. The second example combines three recent research efforts into the use and integration of design generation and analysis methods to show how the DKMS framework facilitates a better understanding of the Generalised Problem as well as the identification of new Specific Problems. The third example describes how the use of design rationale systems might improve the communication across actors, and in that way improves the generation of negotiated knowledge.

3.1. Multi-disciplinary early stage design of complex ships

The first case study to demonstrate the applicability of the DKMS framework is focused on early stage design efforts, based on van Oers et al. (2018). As elaborated in Section 1.2., early stage complex ship design relies on an iterative stakeholder dialogue to elucidate requirements, generate solutions and evaluate technical and financial risks. This iterative process is visualised in Figure 8. For sake of brevity, this paper focuses on the technical specification of the design. Note, the applicability of the DKMS framework to the specification of operational and functional requirements can be shown in a similar manner.

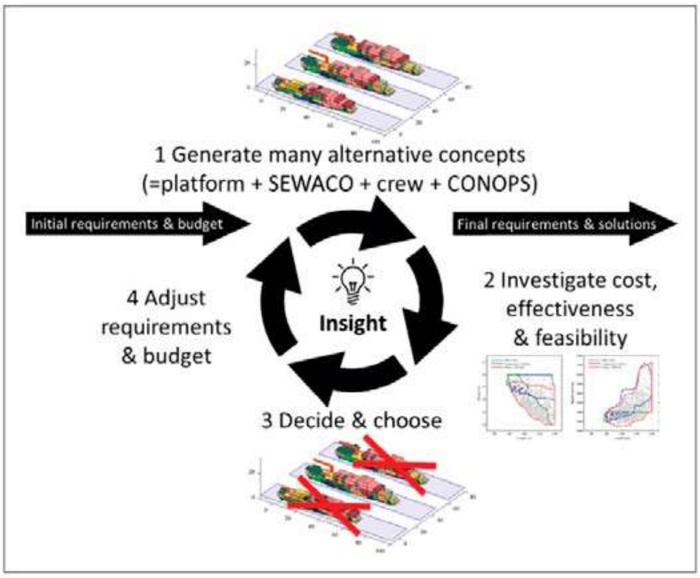


Figure 8.: Iterative dialogue to elucidate requirements, solution and budget (SEWACO = sensor, weapons and command, control and communication systems; CONOPS = Concept of Operations) (van Oers et al., 2018)

The GP of the technical specification concerns the set of technical requirements. The aim of design efforts is to define this set, such that the requirements can be met with technically feasible and affordable concept designs. This means that requirements need to be deconflicted and compromised where necessary.

To evaluate the technical requirements and generate solutions, multiple design disciplines are involved. These design disciplines (e.g. SEWACO (sensor, weapons and command, control and communication systems), Construction, Survivability, Marine Engineering, Naval Architecture) focus on specific issues of the ship design, i.e. different SPs. Some disciplines will focus on specific aspects (e.g. Marine Engineering designing the propulsion system), while others focus on the integration of the overall ship (e.g. Naval Architecture generating General Arrangement Plans). Each design discipline generates solutions (SS) to their SP. This might include SEWACO concepts, construction drawings, guidelines to enhance survivability etc.

Initially, these SSs might not align properly. That is to say, the various technical solutions cannot be integrated in a technically feasible or affordable concept design (GS). Thus the GP is not satisfied yet. By increasing the negotiated knowledge across design teams (by means of the stakeholder dialogue), design disciplines can align. This enhances cross-disciplinary understanding of the overall design problem, and the implications of SS to the GS. Additionally, the iterative dialogue might lead to adjusted requirements and budget to ensure technical and financial feasibility.

Concluding, this case study shows that the DKMS framework provides a way of discussing where design efforts are focused on and that it might be used to analyse and understand ship design processes in the context of techno-social aspects. Such analysis might be used to identify gaps between the GP and GS to identify new SPs to improve on the coherency between solutions.

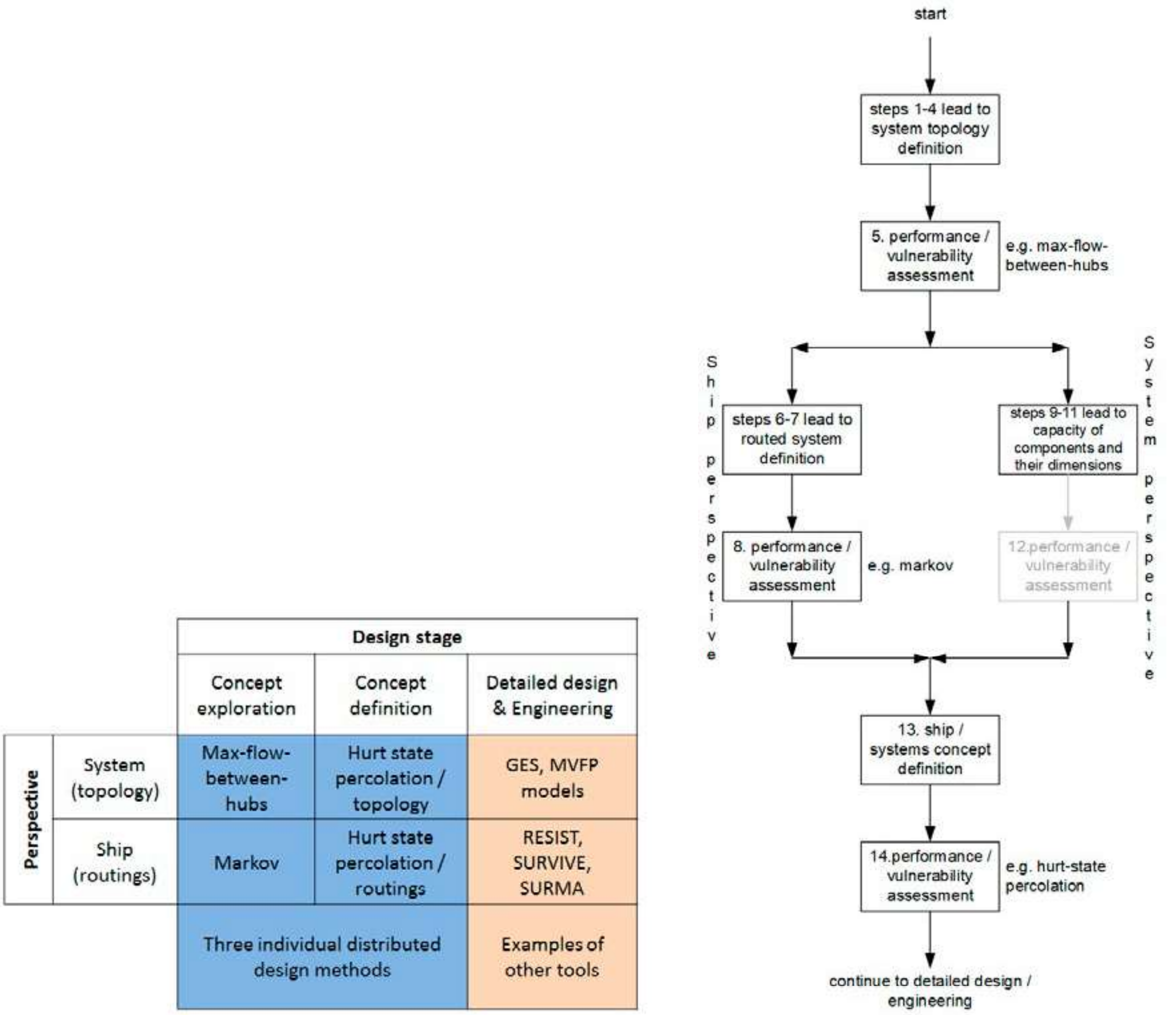
3.2. Integrated concept design generation and analysis methods

The second case study focuses on the integration of concept design generation and analysis methods to support early-stage design via enhanced insights in design problems. Specifically, three pieces of research are discussed in relation to the DKMS framework. First, the integration of three methods related to vulnerability of distributed systems is analysed. Second, the integration of methods with different fidelity is elaborated on. Third, the integration of layout design generation and logistic performance assessment to increase design knowledge is discussed.

Vulnerability assessment

Since naval ships are designed to operate, survive, and win in hostile environments, vulnerability reduction is a major topic of interest during the design of distributed systems (Doerry, 2007; Brefort et al., 2018). This case study is based on previous research efforts, where three individual pieces of research are combined in order to contribute to solving a higher-level design problem (Habben Jansen et al., 2019). The first piece of research considers the design of distributed system topologies (de Vos and Stapersma, 2018). This research quantifies the vulnerability of a topology by means of a network metric that describes the level of connectedness between hubs. This metric is known as 'max-flow-between-hubs' (MFBH). Using a genetic algorithm, a large amount of topologies can be generated within a limited amount of time, allowing design space exploration of topologies during the early design stage. The second piece of research also consid-ers topologies, but focuses on the routing of the topology through the ship, rather than on generating the topology itself (Duchateau et al., 2018). Using a genetic algorithm, this research aims to route the topology through the ship in such way that the vulnerability is as low as possible. This paper uses hurt state percolation (HSP) as the way to assess vulnerability. The third piece of research assesses vulnerability in terms of residual capabilities of the ship as a whole (Habben Jansen et al., 2019). In this research, vulnerability has different levels, such as 'full residual capability' (required after minor damage) and 'minimal residual capability' (required after major damage). Damage is defined in terms of the number of hits, where one hit has a damage extent of one compartment. This is modelled with a discrete Markov chain. As such, this method is referred to as 'Markov' in this paper. For each level of residual capability a requirement for remaining systems and connections is defined. It assumes that a routed topology and a compartment subdivision are available upfront. Contrary to the second piece of research, where the goal is to find the least vulnerable routing, this research aims to elucidate the driving factors for the vulnerability.

For the aforementioned research, the GP is defined as 'design of distributed systems'. Note that the three pieces of research do not span this entire topic. For example, all three methods focus on the early design stage, which leaves detailed design unconsidered. In addition, all methods focus on vulnerability reduction, although from three different perspectives: topologies, routings, and residual capabilities. For each of these three SPs, SSs have been developed: MFBH, HSP, and Markov. Habben Jansen et al. (2019) integrate these three SSs into a GS consisting of a framework (Figure 9.a) and roadmap (Figure 9.b). Compared with the individual SSs, the GS aims to define *how* distributed systems design should be done, rather than *what* should be done. This type of knowledge is mainly about the design activity, while the information from the individual pieces of research particularly consider the design product or concept. Hence, combining specific design information helps in defining generalised design knowledge. This eventually leads to a better understanding of the contributions of individual pieces of research or design methods, as well as capturing, extending, and re-using design knowledge.



		Design stage		
		Concept exploration	Concept definition	Detailed design & Engineering
Perspective	System (topology)	Max-flow-between-hubs	Hurt state percolation / topology	GES, MVFP models
	Ship (routings)	Markov	Hurt state percolation / routings	RESIST, SURVIVE, SURMA
		Three individual distributed design methods		Examples of other tools

(a) Framework for allocating the three individual methods to various stages and perspectives in distributed systems design.

(b) Roadmap for integration of individual methods into distributed systems design.

Figure 9.: Framework and roadmap for integrating individual methods for distributed systems design. Figures adapted from Habben Jansen et al. (2019).

Concluding, this method integration shows that the DKMS framework can be used to structure the way research efforts can be combined in solutions to more overarching problems.

Multi-fidelity models

In the previous case, the analysis methods have been sequentially combined throughout the design process, as shown in Figure 9.b. A different approach is to fuse the results of different analysis methods by means of multi-fidelity models (MFMs). MFMs are defined as models combining low and high fidelity models (Peherstorfer et al., 2018). The high fidelity model ensures the accuracy of the solution, whereas the low fidelity model achieves computational speed-ups. This approach is effective when considering applications which require several model evaluations such as design exploration. This way, more accurate information can be introduced earlier on in the design process. This approach is beneficial when considering the design of novel designs, such as the tumblehome hull of the DDG1000 destroyer, for which traditional low fidelity models (e.g. Holtrop and Mennen resistance calculations) might not give reliable results.

MFMs have been successfully applied in ship design problems requiring the evaluation of computationally expensive models. Gaggero et al. (2021) proposed the implementation of an MFM for the design optimisation of marine propellers. Bonfiglio et al. (2018) proposed a framework for the shape optimisation of 3D super-cavitating hydrofoils by combining data from multi-resolution simulations for the lift and drag coefficients. The aforementioned studies are examples of the applicability of MFMs to design problems. Connecting these MFM research pieces to the DKMS framework, the GP is the design exploration problem based on computationally expensive analysis. The SPs and SSs are the problems and solutions when considering different fidelity. The GS is the MFM which is built by combining the different methods developed as SSs. Overall, the aforementioned cases indicate that computationally expensive problems can be addressed by combining individual analysis methods using MFMs. Regarding early stage ship design, this approach is beneficial for introducing more accurate information earlier on the process to support collaborative decision making by integrating information from various actors and methods.

Concluding, also this method integration shows that the DKMS framework provides a way of discussing how multiple research efforts can be combined to achieve enhanced solutions to higher level problems.

Logistic performance assessment

Droste and le Poole (2020) integrated a layout generation method with a queueing-based logistic performance analysis method. The GP addressed, is the understanding of interactions between the *layout* of a ship and the *performance* of this layout from a logistic point of view. Indeed, the operational effectiveness of logistic processes aboard a ship can have a significant impact on the sizing of the ship, as well as the arrangement of spaces inside the ship. For instance, logistic processes can dictate which spaces are placed adjacent, or drive the size of staircases and passageways. For early stage ship design, the challenges are twofold, which form the SPs:

1. Layout design is challenging, yet required to get insight into the feasibility of requirements and to inform stakeholder dialogues. Hence, layout generation tools need to be responsive to stakeholder needs and provide rapid insights into sizing and integration issues (Andrews, 2011; Duchateau, 2016).
2. Logistic performance assessment typically requires significant input, which is often only available at later design stages. Hence, naval architects need to rely on experience and low fidelity models to assess whether a layout is acceptable from a logistic performance perspective.

To address these two SPs, the following two SSs were utilised:

1. A layout generation method called WARGEAR (le Poole et al., 2022b). WARGEAR is aimed to rapidly develop detailed layout plans of warships, based on a predefined low level of detail layout, and a set of spaces. The aim of this tool is to provide naval architects with real-time insight into sizing and integration issues, which was previously not possible. Indeed, in the past naval architects relied on slow manual (CAD) procedures to develop detailed general arrangement plans of ships to get such design insights.
2. A queueing-based logistic performance method (Droste et al., 2020). The method addresses the gap in early stage low level of detail logistic performance methods. Indeed, logistic performance methods provide static results based on little information, or require significant input to provide highly detailed performance information. Using a queueing-based simulation model, Droste et al. (2020) was able to generate detailed insights into logistic performance of a low level of detail layout.

The GS required Droste and le Poole (2020) to overcome the main methodological mismatch, namely the difference in level of detail. This was achieved by applying the queueing-based method on the layouts generated by WARGEAR. Further, the WARGEAR method needed to be extended to automatically generate a network representation of the layout as input for the queueing method. It was only by actually performing this integration that significant challenges, such as deadlock issues related to the queueing-based method for detailed networks with varying entity demands, were found. Another challenge found is the mismatch in speed. WARGEAR generates results in approximately fifteen minutes, while queueing requires approximately one day to generate a set of simulations. This mismatch in speed was identified as a key aspect for future research, as it poses challenges for the practical use of the integrated method. For instance, is there a need to analyse (almost) balanced layouts only, or is the analysis of less balanced layouts valuable as well? How to select the appropriate set of layouts for time-consuming evaluation? It should, however, be noted that the presented queueing method is a product of research and therefore not optimised for speed and efficiency yet, but there to demonstrate functionality and feasibility.

Besides better understanding the challenges and interactions on the interface between layout generation and evaluation, the method integration also showed benefits for the design of 'internal logistic process driven ships'. Indeed, the combined method was successfully applied to identify sizing and integration issues, such as space entrance positioning and logistic process routing. Such information is key to develop ship layouts that perform well from a logistic performance point of view.

Concluding, also this method integration shows that the DKMS framework provides a way of discussing how multiple research efforts can be combined to achieve enhanced solutions to higher level problems.

Conclusion integrated concept design generation and analysis methods

Figure 10. shows how the DKMS framework can describe how the GP is better understood through the integration of multiple methods, based on the three cases described above. Figure 10.a visualises the understanding of the design problems prior to the integration of these methods, in DKMS framework terminology. Because the individual pieces of research were not reflected to the GS, the GS space is still empty. After integrating the methods, both the GS as the interdependencies between various SPs and SSs are better understood, as visualised in Figure 10.b. Concluding, the three examples of method integration show that the DKMS framework provides a way of discussing and visualising how multiple research efforts can be combined to achieve enhanced solutions to higher level problems. Additionally, the DKMS framework supports the identification of previously unknown interrelations between different SPs and SSs.

3.3. Design rationale to support collaborative design decision-making

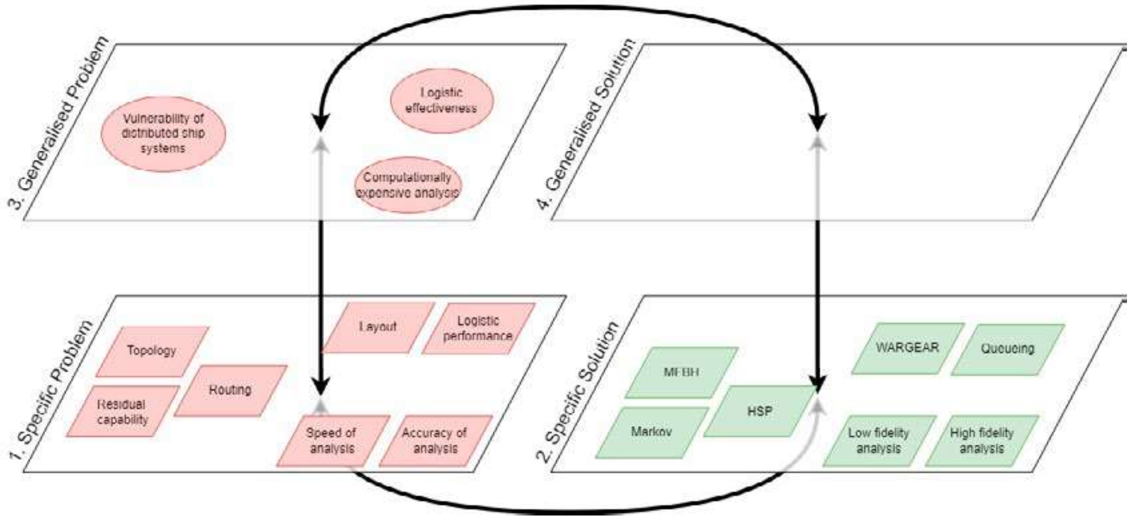
Design rationale comprises design decisions and the justification for these decisions (Conklin and Yakemovic, 1991). In the context of collaborative design decision-making in complex ship design, le Poole et al. (2022a) developed a methodology to capture and reuse design rationale behind ship layout design decisions. The aim of the research is to extend beyond documentation, but to provide explicit benefits for real-time collaborative design processes, such as concurrent design (Bandecchi et al., 2000). In terms of the DKMS framework, the design rationale methodology aims to capture the design rationale behind the transitions between SP–SS, and SS–GS. Such design rationale comprises decisions on, for instance, system properties (e.g. positioning, sizing), interactions between systems (e.g. preferred adjacency and separation constraints), and trade-offs between conflicting design rationale elements.

In the context of the DKMS framework, the design rationale methodology provides, amongst others, the following key benefits to collaborative design decision-making (le Poole et al., 2022a):

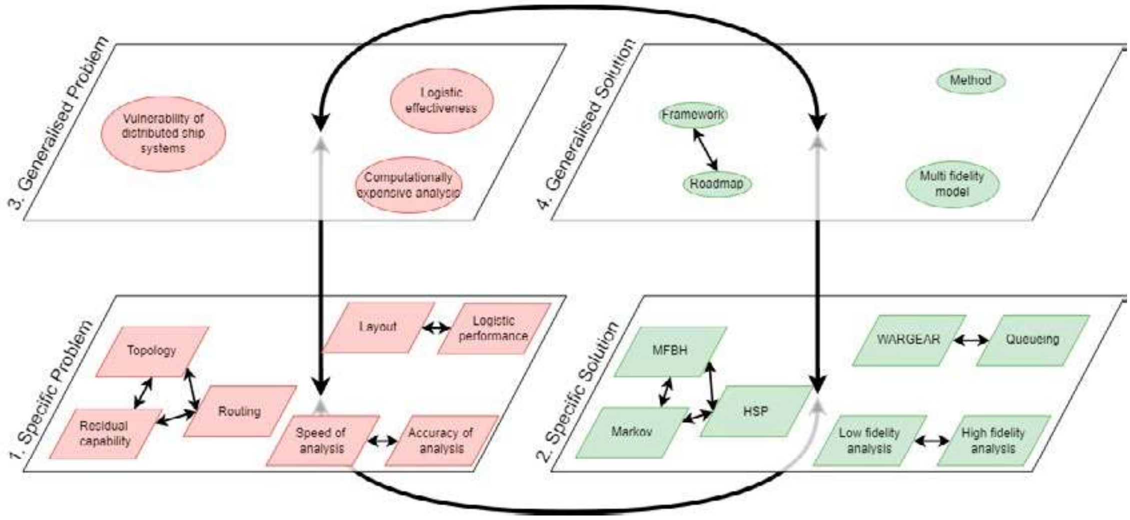
1. The capture of design decisions and justifications underlying the concept design.
2. The identification of conflicting design rationale, and the subsequent trigger to resolve such conflicts through a dialogue between relevant stakeholders. As discussed in Section 1.2., such dialogue creates negotiated knowledge.
3. The retrieval of negotiated knowledge throughout the design process to support design decision-making.
4. The use of design rationale in design tools to generate concept designs during the stakeholder dialogue to support the elucidation of requirements.

Hence, the design rationale methodology is believed to support collaborative design decision-making by enhancing the alignment of perspectives and preferences, thus contributes to the social exchanges described in the DKMS framework, especially these related to the GP and GS.

Concluding, this example shows that the DKMS framework provides a way of discussing where research efforts are focused on, even if the method is not directly focused on generating or analysing concept designs. By considering research in the context of the DKMS framework, both the technical and social aspects of design efforts need to be made explicit. In general, actors need to deliver technically sound solutions, but won't be able to do so if the social aspects are not sufficiently recognised and treated.



(a) Before integration of concept design generation and analysis methods.



(b) After integration of concept design generation and analysis methods.

Figure 10.: Visual DKMS framework representation of evolvement of design knowledge through integration of concept design generation and analysis methods.

4. Discussion

Overall, DKMS framework proposes a design framework for early-stage design of complex vessels. One of the limitations of the case studies presented in this paper is that the DKMS framework has only been applied to study existing research and ship design. However, how the DKMS framework might be applied to actual ship design projects, e.g. as a context or a way of structuring these projects, needs to be considered in future research. The aim of such further research would not necessarily be to implement the DKMS framework in a software, but rather to evaluate if, and how, the DKMS framework can contribute to a better understanding of the complex ship design process in practice. Nevertheless, the elements of the DKMS framework might be used to support, for instance, the decomposition and recomposition of functions and systems.

An important aspect that the DKMS framework highlights is the transition from the SS to the GS. This transition strongly connects to experimental or tacit knowledge (Howells, 1996). Therefore, the DKMS framework has a strong potential to support novice designers who lack tacit knowledge. Therefore, ship design teachers are invited to consider how students are educated and trained in techno-social problem solving (Kana et al., 2016).

From an industry perspective, ongoing developments in line with the DKMS framework are, for instance, Model Based Systems Engineering (Tepper, 2010), and Concurrent Design (Bandecchi et al., 2000). The paper showed how the stakeholder dialogue is essential to solve the wicked complex ship design. Therefore, ship designers, specialists, and other actors are invited to embrace an open attitude to search for unknown design interdependencies with SSs of other stakeholders, through and engaged dialogue. Furthermore, since the practical consequences of utilising the DKMS framework are yet to be determined, ship designers and other practitioners are invited to use the DKMS framework to enhance the understanding of the complex ship design process among stakeholders.

Finally, researchers are invited to position their work in the (expanded) context of the techno-social nature of complex ship design, as well as to contribute to further applications of the DKMS framework.

5. Conclusion

In this paper, a new design framework for early stage complex ship design, called the Design Knowledge Management Square (DKMS) framework, was presented. Complex ship design can be characterised as a wicked problem. Wicked problems in ship design are both technically and socially challenging. Technically, the development and evaluation of requirements and concept designs for complex ships can be difficult, due to the complex interrelationships between and within requirements and concept designs. Socially, complex ship design involves a wide range of stakeholders (e.g. owners, users, designers), who need to align their perspectives and preferences on the design problem. Additionally, various design disciplines are typically involved, requiring alignment of solution generation.

A review of six models for complex ship design, resulted in the conclusion that none of the investigated models explicitly describes the intertwined technical and social aspects of complex ship design, or explains how the understanding of the design problem enhances in multi-actor decision-making. Hence, a framework that explicitly considers the intertwined techno-social aspects of complex ship design and negotiated knowledge between actors involved in decision-making, was needed.

Hence, the DKMS framework was developed, comprising both the technical and social aspects of multi-actor collaborative (design) efforts in complex ship design. The DKMS framework comprises four main elements. The overall design problem and actors' perspectives on that design problem are described by the Generalised Problem (GP). Specific Problems (SP) is a portion of, or view on, the GP from the perspective of an actor. This actor generates a Specific Solution (SS) to the SP. Eventually, SSs are integrated into a Generalised Solution (GS). Transitions between these four elements comprise of both technical (e.g. generating drawings) and social aspects (e.g. stakeholder dialogue).

Three case studies were conducted to show how the DKMS framework might be applied to complex ship design. The first case study show how the DKMS framework can be used to describe and analyse multi-disciplinary design of complex ships. The second case study shows how the DKMS framework stimulates the integration of design methods to enhance design knowledge. The third example shows how design rationale capturing and reuse can support multi-actor decision-making, in the context of the DKMS framework.

Based on these case studies, the DKMS framework can be used to describe, understand, analyse, and support complex ship design problems and solutions in techno-social terms. In addition, the application of the DKMS framework is expected to benefit complex ship design as it stimulates the creation of negotiated knowledge, which is ultimately the basis for multi-actor decision-making.

5. Disclaimer

The content of this paper is the personal opinion of the authors. Specifically, it does not represent any official policy of DAMEN Naval, the Netherlands Ministry of Defence, the Defence Materiel Organisation, or the Royal Netherlands Navy. Furthermore, the results presented here are for the sole purpose of illustration and do not have an actual relation with any past, current or future warship procurement projects at DAMEN Naval or the Defence Materiel Organisation.

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