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ON-THE-FLY DESIGN RATIONALE TO SUPPORT REAL-TIME COLLABORATIVE NAVAL SHIP LAYOUT DESIGN

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ABSTRACT

This paper presents a new design rationale methodology to support collaborative design decision-making during early stage complex ship design. The nature of collaborative design is described and the need and key challenges of design rationale capturing and reuse are identified.
Subsequently, the methodology is developed to overcome these key challenges. A primary characteristic of the methodology is it's integration with design tools to reduce intrusiveness and enhance usefulness during collaborative design sessions.
Finally, a case study was used to demonstrate the usefulness of the developed design rationale ontology, a critical step in providing designers an improved capability to capture and reuse design rationale during collaborative design decision-making.

KEY WORDS

design rationale; early stage design; warships; complex ships; collaborative design.

1. INTRODUCTION

The application of concurrent engineering or concurrent design processes in complex ship design indicates that ship design is seen as a field of multi-actor decision-making. Some recent examples of concurrent design in Dutch ship design are the yacht builder Feadship (Feadship, 2017) and the Dutch Ministry of Defence (NIDV, 2021). Such concurrent and collaborative design processes are applied to involve all relevant stakeholders and design disciplines in the decision-making. The aim of concurrent design is to better integrate disparate knowledge, experience, and preferences, as well as to build consensus among stakeholders (Bandecchi et al., 2000).

This is essential, since early stage naval ship design has frequently been described as a wicked problem (Andrews, 2011, 2018c; Shields et al., 2016; Duchateau, 2016), as it is not only the product (i.e. the ship) which is still fluid, but more importantly the required performance (i.e. the requirements) which are fluid (Duchateau, 2016). From a general multi-actor decision-making perspective, wicked problems can be described as a type of problems where there is a lack of consensus on both the problem and solution to the problem (see for instance the public debate on COVID-19) (Roberts, 2000). Discussion, persuasion, and bargaining (Wolff, 2000) are required to resolve conflicts and to create negotiated knowledge between stakeholders. Such negotiated knowledge is the base for collaborative decision-making (De Bruijn and Ten Heuvelhof, 2008). Indeed, only when there is agreement on the problem, there can be agreement on the solution. In naval ship design, wicked problems involve an inherent relationship between defining requirements and generating concepts designs to fulfil these requirements. Such concept designs are essential to investigate technical and financial feasibility of these requirements (Van Oers et al., 2018) and are used in the stakeholder dialogue to elucidate new or updated requirements (Andrews, 2018c; Van Oers et al., 2018). As such, ship design can be studied from both a technical design perspective and a collaborative (design) decision-making perspective.

This research specifically focuses on ship layout design, as layouts 1) are key in communication during ship design, 2) involve many multi-disciplinary, technical or value-based trade-offs, and 3) are input for various design disciplines (Carlson and Fireman, 1987; DeNucci, 2012; Duchateau, 2016; Van Oers et al., 2018). Earlier research in early stage ship design has focused on developing tools and processes to help naval architects generate concept designs and enable earlier more complex design analysis (e.g. routing of distributed systems, vulnerability assessment). Over time, such tools have become increasingly applicable for real-time collaborative design-decision making by providing real-time insights into design drivers and consequences of design decisions (Le Poole et al., 2020; Le Poole et al., 2022). This reduces the amount of 'speculation' when stakeholders are together and make decisions on the way forward. Thus, making decision consequences tangible could improve collaborative decision-making (Wolff, 2000; Van Oers et al., 2018). This requires 1) that design rationale, i.e.

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reasoning behind design decisions (Conklin and Yakemovic, 1991; DeNucci, 2012), must be made explicit and 2) that the impact of such rationale is evaluated.

Since design is, partly, a creative and intuitive process (Dorst and Cross, 2001; Durling, 1999), it might be hard to make design rationale explicit and precise (Shum and Hammond, 1994; Knudsen et al., 2020). Yet, such design rationale is key in the communication between designers and other stakeholders (e.g. requirement owners, other design departments, etc.) (MacLean et al., 1991). DeNucci (2012) and Gillespie (2012) show that design rationale in ship layout design 1) can be made explicit, 2) can be used to analyse designs, and 3) can be used to identify design drivers.

However, how such design rationale is best captured and reused on-the-fly during the design task, in the context of real-time collaborative design, is yet to be fully understood. This paper:

1. investigates which requirements a design rationale methodology needs to meet;
2. proposes a methodology to fulfill these requirements; and
3. demonstrates an initial implementation of this methodology.

The structure of the paper is as follows. Section 2 elaborates on the nature of complex ship design and the challenges of design rationale application. Subsequently, requirements for a new design rationale methodology for collaborative early stage complex ship design are provided. Then, Section 3 presents this novel methodology. In Section 4 the developed methodology is used during the design of a notional Oceangoing Patrol Vessel. The paper closes with conclusions in Section 5.

2 BACKGROUND

2.1 Ship design as a collaborative decision-making process

Decisions are an integral part of design (Dorst, 1997). Even the first sketches include decisions on 'design style' (Andrews, 2018a; Pawling and Andrews, 2011; Pawling et al., 2013). Indeed,

> "*decisions help bridge the gap between an idea and reality. They serve as markers and units of communication to identify the progression of a design from initiation, through implementation to termination and they exhibit both domain-dependent and domain-independent features*" (Mistree et al., 1993).

Such decisions are usually made in a process involving multiple stakeholders (MacLean et al., 1991). Naval ship design also involves many stakeholders, comprising amongst others various design disciplines (e.g. naval architects, structural engineers, marine engineering specialists) as well as (representatives of) customers (e.g. government, navy, and companies), with the added complexity of political approval and procurement procedures (Andrews, 2011, 2018b; Knegt, 2018; Van Oers et al., 2018). Therefore, it is worthwhile to investigate ship layout design decision-making from a multi-actor perspective.

General multi-actor decision-making theory...

Teisman (2000) compares three models to represent decision-making processes, which can be used to analyse decision-making: phases, streams, and rounds. The phase model describes the decision-making process as a set of successive and distinctive stages, and focuses on decisions taken by a focal actor. The streams model describes decision-making as making the connection between streams of participants, problems and solutions, and focuses mainly on these connections. The rounds model considers decision-making to take place in 'rounds' in which 'actors introduce combinations of problems and solutions, and create progress through interaction', and focuses on the interaction between actors. In each round, new actors can appear, the problem and solution definition can change, and the rules of the game can alter.

Multi-actor decision-making deals with decision-making between stakeholders in a network interrelationship. Contrary to hierarchies, decision-making in networks strongly depends upon the behaviour of stakeholders (De Bruijn and Ten Heuvelhof, 2008). Figure 1 illustrates dependencies between actors in a hierarchy and a network. Communication between stakeholders is key to resolve differences of opinion and conflicts (Hempel and Lammerant, 2015). Differences of opinion can be solved via discussion and persuasion. Conflicts result from different interests of stakeholders and need bargaining to be solved. An important part of bargaining is that stakeholders should offer compensation to other stakeholders who accept a less than optimal solution in favour of a better solution for the former (Wolff, 2000). In addition, De Bruijn and Ten Heuvelhof (2008) explain that the decision-making process may also lead to enrichment. Enrichment is achieved when stakeholders exploit the wicked problem such that synergy is created between raised issues. Decisions in multi-actor decision-making are made based on negotiated knowledge, that is, common knowledge is created through interaction and discussion among stakeholders (De Bruijn and Ten Heuvelhof, 2008). Creating negotiated knowledge can therefore be seen as a learning process of individual stakeholders (Partidario and Sheate, 2013).

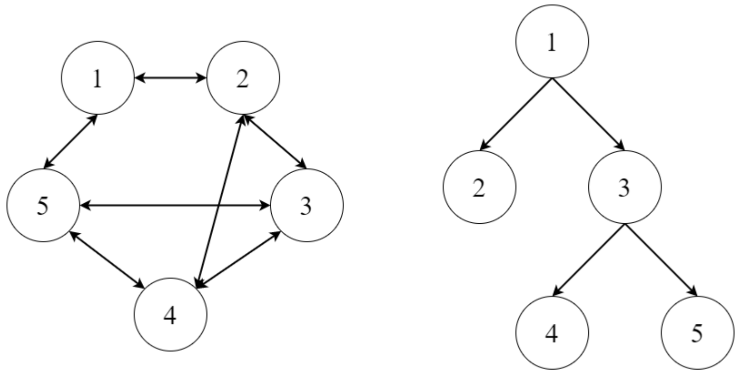

Figure 1: Hierarchy versus network. Nodes represent actors, arrows indicate dependence between actors.

The wicked problem, as described above, is a type of problem where stakeholders lack consensus on both the problem and the solutions. To account for all relevant and different perceptions of stakeholders, the problem definition is not fixed, but only defined in broad terms. Such problem definition mainly considers the links between the views of stakeholders, i.e. it is used to describe the commonalities between the perceptions of stakeholders where potential ground for consensus can be found. The fluidity of the problem definition can challenge the applicability of linear problem solving approaches, e.g. problem specification, data gathering and analysis, solution formulation and implementation (Roberts, 2000; De Bruijn and Ten Heuvelhof, 2008).

Information is not only used to solve problems, but can also be used to influence stakeholders' perception of the problem. Therefore it is necessary to consider both the quality of information and the influence of using that information (De Bruijn and Ten Heuvelhof, 2008). According to Partidario and Sheate (2013) knowledge is constructed by learning trough an active, mental process of development. Knowledge is formed when information is interpreted by individual human and related to a context and anchored in the believes and commitments of those individuals. As a consequence, decision-makers need to *learn* what the impact of their requirements and decisions is, i.e. this cannot be simply transferred from an expert to stakeholders (e.g. via informing or consulting strategies (Michaels, 2009)). Learning is a fundamental human process that helps update and evolve experimental knowledge of previous designs, processes, events, actors, environmental concerns (Duffy, 1997). Duffy (1997) continues "learning alters a human's state of knowledge and hence directly influences the human ability to solve problems". Enrichment is a form of learning that can occur in multi-actor decision-making (De Bruijn and Ten Heuvelhof, 2008). Therefore, approaching design from a multi-actor decision-making perspective is essential to tailor design support methods to this learning process that underlies the creation of mutual consensus.

...applied to complex ship design

As mentioned above, early stage complex ship design is well recognised to be a wicked problem (Andrews, 2018c; Duchateau, 2016). Designers need to ensure coherency of the concept design and to inform stakeholders on the impact of their requirements, to elucidate new or updated requirements (Andrews, 2018c; Van Oers et al., 2018). Although keeping the same key stakeholders involved during early stage design (Van Oers et al., 2018), new actors will likely appear during a project, due to extensions of project teams, retirement, job changes, etc.

Various models have been proposed to describe ship design processes, e.g. the well-known 2D 'design spiral' (Evans, 1959) and Andrews (1981)'s 3D design spiral. See Pawling et al. (2017) for a discussion of these models. Ship design has also been described as a process of distinctive and successive preliminary design, contract design, detailed design phases (Duchateau, 2016). These stages might be related to more distinct political phases or gates in naval ship design (see for instance Van Oers et al. (2018)). On the level of collaborative design, Teisman (2000)'s round model might be applied. Indeed, design (review) sessions are not only intended to detect flaws in the concept design, but also to align designers and design disciplines (Van Van Oers et al., 2018), i.e. to create enrichment and negotiated knowledge as a basis for decision-making. This is explicitly pursued in concurrent design processes (Bandecchi et al., 2000). In later design stages (e.g. post-contract) design reviews are often more formalised.

If decision-making can be described by the rounds model, understanding the role of perceptions and the decisions that are taken in the process requires the gathering of all decisions. A-priori determining what the key decisions are is not possible, since there is no central decision or central problem to be solved (Teisman, 2000). In complex ship design, design insights and importance of specific decisions can typically only be determined post-priory or interactively due to the complex relationship between the design and performance space (Pawling, 2007; Duchateau, 2016), as depicted in Figure 2.

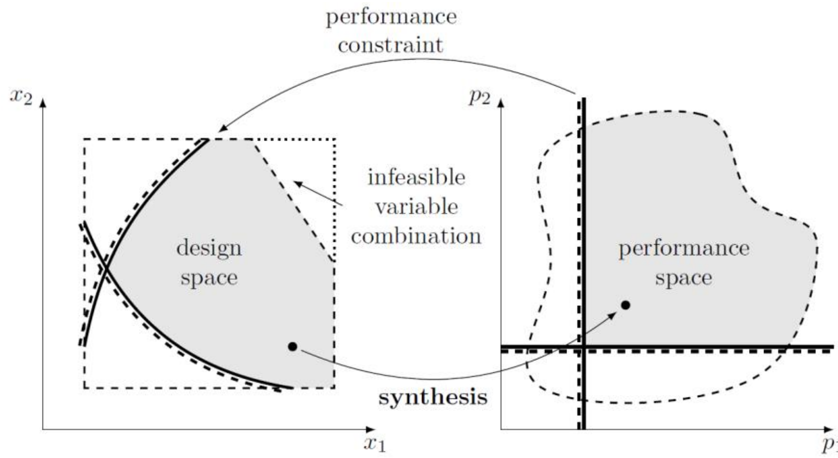

Figure 2: Complex interactions between design and performance space (Duchateau, 2016).

(Watson, 1998, p20) states that naval architects should devote "a lot of time and attention" to the accumulation of data relevant to their work, where the boundaries of their interest should be set wide. The naval architect can use such information to solve emerging design problems. However, this information might also become useful in different rounds of the multi-actor decision process, i.e. to be used to resolve differences of opinion and conflicts. Also, Wolff (2000) found that decision-making in ship design could be improved by making information widely available to all stakeholders. However, proper interpretation of all information in the context of the design problem can be difficult.

2.2 Ship design as a creative process

The nature of early stage ship design is dynamic and exploratory since it requires the elucidation of requirements via the generation and discussion of concept designs with stakeholders. Dorst and Cross (2001) describes creative design to be the intertwined co-development of problem formulation and solution ideas, which reflects the nature of requirements elucidation early stage complex ship design (Andrews, 2018c).

This means that design tools that support decision-making in early stage design should have the following characteristics (Andrews, 2011; Duchateau, 2016):

1. *Believable and coherent solutions*, that is, generated solutions should be technically feasible and sufficiently descriptive (e.g., they must obey the laws of physics, the basic principles of naval architecture, and the necessary rules and regulations). Additionally, solutions should be presented in a format that can be understood by stakeholders (Kossiakoff et al., 2003). For complex ship designs, the availability of 2D or 3D layout plans is essential, since much of the information, requirements, and performance is based on spatial data. Therefore, problem solving often involves not only numbers, but also architectural aspects (Andrews and Dicks, 1997; Pawling, 2007; Van Oers, 2011; Van Oers et al., 2018; Duchateau, 2016).
2. *Open and responsive methods*, that is, the opposite of a "black-box" or rigid decision systems. Tools and methods should respond to those issues that are deemed important to the stakeholders, in a timely manner (Van Oers et al., 2018). Indeed, slow tools can damage the dynamic design process, resulting in stakeholders to rely on quicker, but not necessarily better, tools to keep up and support decision making by providing insight into design drivers (Duchateau, 2016).
3. *Creative approach*, that is, encouraging radical "out-of-the-box" solutions and a wide design exploration to push requirement elucidation boundaries. At the same time, solutions should be believable enough to prompt stakeholders into conversations on (rather than scrutinising) those designs.

McCall proposes to intertwine ideation (i.e. generation of (novel) ideas) and evaluation (determination of value of these ideas), to promote creativity in design. Such intertwining can take two forms (McCall, 2010):

1. A discussion among designers in which verbal evaluations of proposed ideas prompt them to devise new ideas. This involves feedback from *speculation about consequences* of design decisions for implementation and use.
2. Involving feedback resulting from actions, especially the actions of implementation and use, to prompt designers to devise new ideas. In the case of collaborative design decision-making, such feedback might originate from stakeholders in the dialogue and design tools used to evaluate design decisions while they unfold. Rationale methods

supporting feedback-driven dialogue need to be process-oriented (McCall, 2010), i.e. comprise temporal and logical relationships between rationales, ideas, and consequences.

Although design tools can be supportive to the design process, they are not decisive. Indeed, the importance of the human designer in decision-making is underlined by the definition of *design*. According to Dorst (1997, p.35) design is "*a thought process aimed at building a network of decisions that form the thought-construct 'product', which can be instantiated in the material world*". Thus, decision-making is inherently part of design and therefore the objective of the naval architect is to make the best decisions possible with the (frequently limited) information at hand (DeNucci, 2012). Due to the iterative, non-linear nature of early stage ship design (Pawling et al., 2017), design decisions might have to be reconsidered later in the design process. Indeed, in the case of an emerging design issue, a value-based evaluation of the design decision is required, before changing the concept design (Van Oers et al., 2018; Pawling et al., 2017; Andrews, 2021). This requires knowledge on the reasoning behind past design decisions, i.e. design rationale. Design rationale comprises design changes, as well as the justification of these changes. This justification, or intended goal, might be complex and tied to other goals (e.g. changes to the layout, to improve stability, vulnerability, primary system performance, etc.). However, it is typically this justification that is lost during the process. Therefore, it is necessary to investigate why design rationale is frequently insufficiently captured and how this situation can be improved.

2.3 Design rationale in ship design

Design rationale in practice
Ball et al. (2001) defines design rationale to

> "*encompass the documentation of the active processes of reasoning and decision-making that led to the artefact design — including the justification for design decisions, records of design alternatives considered and trade-offs evaluated, and details of the argumentation and communication processes associated with design work*."

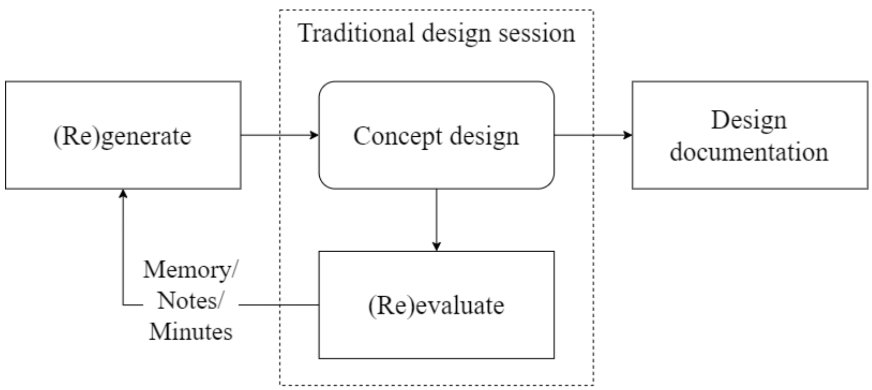

Figure 3: Representation of activities in a traditional ship design process

In today's ship design processes various bits of design rationale are contained in minutes of meetings, emails, and system description documents (to name but a few). The main source for design rationale is the human designer, who keeps (implicitly or explicitly) track of design decisions, as well as other factors that might have (negatively) impacted previous design decisions. Examples of these factors are the organisational (e.g. team dynamics) andtemporal (e.g. time pressure) context of decisions, as well as design drivers of past projects (e.g. a past budget violation might lead to additional attention for the financial part of a current design project).

Figure 3 represents a traditional ship design process and contains the following principle design activities:

1. **Generation**. Prior to design sessions, designers generate concept designs based on predefined or assumed requirements and preferences, to provide insight in consequences of these requirements (Van Oers et al., 2018).
2. **Evaluation**. During the design session two or three-dimensional views and performance evaluations (e.g. speed, stability, etc.) of the concept design are evaluated and result in the expression of additional or revised requirements and preferences. Designers rely on experience and reasoning to estimate whether these preferences can actually be implemented and how that might be done. It's only when the designer returns to the drawing table (i.e. *Generation*) when the actual impact of the design decisions becomes known. Often multiple variations to solve a problem might be a way to overcome the "assumptions''. For example, a stability problem could result in several options being investigated for the next step (e.g. wider hull, lower CoG, or combination of both).

3. **Design documentation**. Typically, design documentation is done via reconstruction of the concept design, with support of minutes of meetings, notes, and the designer's memory. Capturing design rationale separately from design tools leads to lack of context of decisions (Pawling, 2007, p120).

As illustrated above, an explicit focus on design rationale in early stage ship design is missing, partly because design rationale itself is no direct deliverable in the ship design process (DeNucci, 2012). Indeed, the main focus lies on the concept design (in the form of a variety of drawings and calculations) and a consistent set of requirements (DeNucci, 2012; Van Oers et al., 2018). To enhance this situation, Pawling et al. (2017) states that "the provision of an automatically generated logbook [has been long seen as desirable in computer-aided ship design]. This would provide inexperienced [and experienced] designers with an invaluable tool when reviewing and reassessing previous design decisions and provide an audit trail when used in anger. Given the interrelation between so many functions, such audit trails would be particularly helpful in identifying sources of unexpected or undesired changes to the model and further assist in better design assurance in early design decision-making." Yet, such logbook would only record consequences of decisions - not its supporting rationale.

The case for design rationale

To make the best decisions, the naval architect needs to be aware that a decision is made in the first place, as well as of the consequences of these decisions, the possible alternatives, assumptions, and the reasoning behind the decisions (DeNucci, 2012). Such insight is a key part of knowledge obtained through design. Indeed, Andreasen et al. (2015, p.30) states:

> "*Initially the product is based on assumptions concerning functionality and properties, its ease of production and assembly, and its reliability and robustness. The design activity should lead to factual insight into these aspects, outlining technological concerns as well as the risks associated with launching the product.*"

Being aware of the reasoning behind decisions can be a challenge because such reasoning is often based on experience and intuition, i.e. the reasoning is implicit. However, to be able to explain the decision to others, the reasoning (i.e. design rationale) needs to be made explicit. *Design rationale* research offers possibilities and benefits to support designers to express and reuse design reasoning.

Benefits of design rationale

If the reasoning behind a decision is known, it provides insight into the decision made. This might be useful for documentation purposes and to inform stakeholders. Design rationale explicitly attempts to capture the reasons behind design decisions (DeNucci, 2012; Conklin and Yakemovic, 1991). However, explicitly thinking about the rationale also supports the decision making process, as decision makers become more aware of their actions (MacLean et al., 1991; Lee, 1997). Capturing rationales can provide a history, justification, and a baseline for technical comparison of design attributes across relatively similar designs (DeNucci, 2012). In addition, the (re)use of rationale in design may offer opportunities to improve the design process (DeNucci, 2012). Design rationale is invaluable as an aid for revising, maintaining, documenting, evaluating, and learning the design (Burge and Brown, 2000). According to Lee (1997), design rationale can be used to provide design support, maintenance support, learning support, and documentation support. The use of design rationale improves the effectiveness of collaborative decision-making (Falessi et al., 2006).

In the case of early stage ship design, capturing design rationale is expected to benefit the whole ship design process. During pre-contractual design efforts, it provides support to the design team by providing insight into their own design considerations (Stroo-Moredo and Krikke, 2015). During post-contractual design efforts, design teams become larger, and rely on the output of the pre-contractual design process. Besides the pre-contractual benefits, design rationale can serve as memory support of design reasoning across different design phases and teams (Stroo-Moredo and Krikke, 2015).

Challenges of design rationale

Although design rationale capturing and reuse has various benefits, it is not widely applied. Indeed, design rationale methodologies need to overcome various challenges. Design rationale methodologies can be:

1. Intrusive in the design process, and thus leading to designer resistance to use such tools (Burge and Brown, 2000).
2. Seen as a separate process from the designing the artefact, and therefore documenting decisions can impede the design process (Fischer et al., 1991). This is in line with traditional ship design processes, as described above.
3. Time-consuming (Burge and Brown, 2000) and therefore seen as expendable if deadlines are near (Conklin and Yakemovic, 1991). This can be extended to collaborative design sessions, since meetings typically are time-constrained and focused on the progress of the concept design.
4. Not cost-effective, e.g. if the designers bearing the costs are not the same as the benefiting persons (Lee, 1997).

This can cause designers to be reluctant:

1. To take the time to document the decisions they did not take, or took and then rejected (Conklin and Yakemovic, 1991). That is, they are less willing to spend time on ideas considered invaluable. However, the reason why these ideas are considered 'invaluable' can be 'valuable' information at a later stage (e.g. rework of the design).
2. To record (controversial) decisions to avoid scrutiny at a later point in time (Horner and Atwood, 2006).
3. To use a design rationale tool besides other design tools (Ball et al., 2001).

From these challenges can be concluded that a design rationale methodology 1) needs to add clear direct advantages to the collaborative design process itself, above the (natural) long term benefits and 2) might best be integrated with ship design tools. Such integration would make design rationale a byproduct of design activities and reduce intrusiveness (Burge and Brown, 2000; Chen et al., 1990).

2.4 Research on design rationale in ship design

In ship design, design rationale-related research has focused on[3]:

1. Capturing design rationale (DeNucci, 2012). DeNucci (2012) developed a design rationale capturing methodology based on the principle of triggering individual designers by presenting non-conventional concept designs and asking what they did or did not like about specific design aspects. How capture compromises between conflicting rationales was kept explicitly out of scope, but is a key part of design decision-making (DeNucci, 2012; Andrews, 2018b; Duchateau, 2016).
2. Using system interrelationships to identify design drivers prior to arranging systems in a layout (Gillespie, 2012; Pawling et al., 2015). Network centrality metrics were used to identify the systems with (potentially) the highest impact on the layout.
3. Using system interrelationships to generate concept designs (Gillespie et al., 2013). Predefined networks can be used as input for the actual arrangement process (Andrews, 1985; Esbati, 2018). These examples show that it possible to (automatically) generate layouts that contain, for instance, a minimal number of unsatisfied required adjacency and separation interrelationships.
4. Using system interrelationships to evaluate generated concept designs (Roth, 2016; Pawling and Andrews, 2018). Similar to above, network centrality metrics were used to rank concept designs (Roth, 2016) and to identify key systems (Pawling and Andrews, 2018). Pawling and Andrews (2018) stresses the importance of node compliance to the actual systems in the concept design for understandability of centrality values and proposes to use centrality metrics to sort design options for design support.

These examples of research primarily focus on the relations within design rationale (e.g. required adjacency between systems). How design rationale is best captured and reused in collaborative complex ship layout design has not yet been investigated. To fill this gap, a new methodology tailored towards this goal needs to be developed.

2.5 Requirements for methodology

Based on the various views on collaborative design decision-making, the ship design process, the following requirements are set for a new design rationale methodology.

RQ1: *The methodology must be applicable for early stage collaborative design activities and promote feedback-driven conversations*, that is, it is to support the creation and capture of negotiated knowledge.
RQ2: *The methodology must enable the capture and review of design decisions, the rationale behind these decisions, and temporal relationships between design decisions*, i.e. it must capture what is changed, how, why, and when.
RQ3: *The methodology must provide immediate rationale-based feedback to increase the benefits relative to the costs of capturing design rationale*, to enhance the designers' willingness and ability to spend effort in using the methodology.
RQ4: *The methodology must be generic*, i.e. applicable for all ship types, to allow a wide and standardised application in ship design processes.
RQ5: *The methodology must be easy to use and integrated within design tools*, 1) to reduce intrusiveness and thus to improve the potential to be accepted by designers and 2) to enhance the context of captured design rationale.

[3] For an elaborate review of past research on design rationale, see DeNucci (2012).

3 PROPOSED METHODOLOGY

In this section the proposed methodology to fulfill the set of requirements is elaborated. The section is structured around the following questions:

1. *How* is the captured design rationale reused? That is, which services is the design rationale methodology to provide? This is a key question, since the design of a design rationale system is mainly determined by the services it provides (Lee, 1997). Indeed, the answers to the following two questions are dependent on the intended use of the rationale methodology.
2. *What* design rationale needs to be captured and how to represent this design rationale? That is, what decisions are made in early stage ship design? To enable a computer to provide services, a consistent ontology needs to be developed that enables designers to capture design rationale in a structured manner.
3. *How* to integrate the design rationale capturing and reuse methodology into early stage ship design sessions and tools?

3.1 How to reuse design rationale

A key aspect, and indeed a requirement for the new methodology, is provide sufficient benefits to outweigh the costs of capturing rationales. For a designer these costs might be related to cognitive, capture, retrieval, and usage barriers (Horner and Atwood, 2006).

The benefits of design rationale methodology are twofold. First, benefits can be an implicit by-product of using a design rationale methodology. For instance, being forced to express design rationale can improve decision-making, even if the methodology focuses on documentation (Shipman and McCall, 1997). Second, benefits can be explicitly intended services (Lee, 1997). This paper focuses on the latter category and proposes the following design support services.

1. *Design rationale capture, storage, and retrieval*. Design rationale can be automatically generated from, for instance, design documentation (Lee, 1997), such as ship design rules and regulations. However, the proposed methodology is to capture evolving design considerations emerging from collaborative design sessions. Hence, designers need to be able to capture design rationales as these emerge (in situ). Further, captured design rationale needs be accessible and retrievable, e.g. to review past design decisions or to recall the justification and context of these decisions.
2. *Design guidance*, that is, to generate design insight based on captured design rationale, to inform the collaborative design session on the impact of requirements and preferences.
    - Design rationale *satisfaction* and *consistency*. Satisfaction expresses whether a single design rationale is achieved in the current concept design. Consistency can relate to the syntactic and semantic content of a captured design rationale (DeNucci, 2012), but in this paper it refers to the consistency of the set of rationales. That is, it expresses which rationales conflict directly or indirectly. A direct conflict is a conflict between two rationales (e.g. A<B and B<A). An indirect conflict is a conflict within a larger set of rationales (e.g. A<B, B<C, and C<A), i.e. the set does not comply to the transitive property.
    - Design rationale-based *Measures of Performance* (MoPs) are concept design evaluation functions which use captured design rationale. Such MoPs can provide high level information on the quality of the concept design and be used to visualise the impact of different trade-offs between conflicting system arrangements.
    - Design rationale-based *automated, real-time, concept design generation*. Such tools support the collaborative decision-making process by providing a way to quickly explore viable solution alternatives. This would overcome the need to wait for another "round", e.g. design session, to further explore the most feasible path or solution. For instance, if the most viable solution to a stability issue can be identified during a design session, direction for more detailed analysis can be provided. In addition, stakeholders are better aligned, since they both are aware of the design problem and the potential solution.
      Similarly, (semi-)automated layout design tools (e.g. WARGEAR (Le Poole et al., 2020; Le Poole et al., 2022)) might be used to evaluate the impact of an evolving set of design rationale on the overall concept design, by generating alternative concept designs that satisfy captured design rationale. Integrating elucidation of requirements and design rationale with evolvement of the concept design during collaborative design is expected to benefit mutual understanding (Le Poole et al., 2020) and is in line with McCall (2010)'s proposal to intertwine ideation and evaluation, see Section 2.2. How such tools are best used during collaborative design decision-making remains a topic for future research.

Specific example for MoPs (Bullet 2)
Examples of design rationales in ship layout design are the relative positions between systems (DeNucci, 2012). A subset of all systems could be preferred to be adjacent to improve logistical performance. In this case, a design rationale-based MoP could calculate the Manhattan distance between this subset of systems. Note that more elaborate MoPs can be developed, see

for example Le Poole (2018). Figure 4 shows three different layouts, in which arrows indicate preferred logistic adjacency relationships and the MoP represents the Manhattan distance between systems (Table 1).

Since these MoPs are dynamic (i.e. capturing new design rationales changes the input of MoPs), MoP-values might not directly comparable between designs. In the example in Figure 4, the MoP for Layout 2 is higher than Layout 1, but it also considers an additional relationship. Similarly, the MoP for Layout 3 is lowest, but considers a partially different set of systems. Therefore, MoPs might be best suited to provide design guidance from the current state of the concept design, i.e. designers might use MoPs to identify how to improve the current concept design. Additionally, previous concept designs might be reevaluated using an up-to-date set of design rationales.

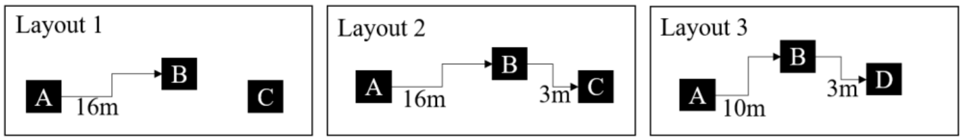

Figure 4: Dynamic MoP, calculating Manhattan distance using design rationale related to logistics for three layouts.

Table 1: Design rationale-based MoP. Manhattan distance for three layouts in Figure 4.

System relationship	**Layout 1**	**Layout 2**	**Layout 3**
d(A-B) [m]	16	16	10
d(B-C) [m]	-	3	-
d(B-D) [m]	-	-	3
MoP: Total Manhattan distance [m]	**16**	**19**	**13**

Besides MoPs that use specific design rationales to provide information on the quality of the concept design, the whole set of captured design rationales might be evaluated using a range of network metrics. Examples are network centrality metrics, which can be used to identify systems likely to drive or constrain a ship arrangement, as demonstrated by (Pawling and Andrews, 2018; Gillespie, 2012).

3.2 What design rationale to capture and how to represent it?

Lee (1997) expected that rationale representation would not provide large challenges, compared to, for instance, cost-effective implementation of design rationale systems. For this reason, the rationale representation for ship layout design developed by DeNucci (2012) has been adapted and extended. This rationale representation is a semi-formal representation, which includes both predefined, structured elements (formal) and natural, unstructured elements (informal). Formal elements are typically better 'understood' by computers, while informal elements allow designers to express themselves with limited effort, thus reducing the costs of rationale capturing (Lee, 1997).

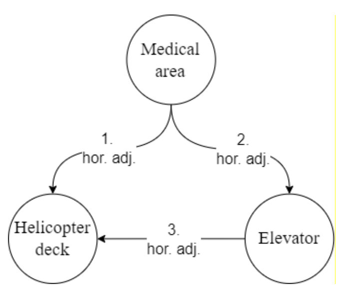

Figure 5: Required connectivity between a medical room and a helicopter deck, comprising a compromise between interaction 1. and interactions 2. and 3.

The following design rationale categories are defined:

1. A **System Property** is a (required or actual) quality or characteristic of a system and its justification. Examples of System Properties are required sizing (e.g. volume, area, aspect ratio, alternative positions) and preferred global positions (e.g. on deck 3, as high as possible).
2. An **Interaction** is a preferred (spatial) relationship between two (or more) systems (DeNucci, 2012), or System Properties. Additionally, an interaction comprises its justification. An example of an interaction is: *the ammunition store should be adjacent to the gun* [relation], *to reduce dangerous transport of ammunition through the ship* [justification].

3. A **Compromise** is the preferred solution to a set of conflicting or competing interactions (DeNucci, 2012) or System Properties and its justification. For example, consider the required connectivity between a helicopter deck and the medical room in a frigate, depicted in Figure 5. This situation comprises three interactions (1.-3.). The related compromise is the preferred set of interactions, where the naval architect is to choose between set A = {interaction 1.} and set B = {interactions 2. and 3.}. Choosing set A might be justified by reasons as 'reduced spatial impact' and 'less time to medical room'.
4. Designers can use **Notes** to explain design considerations not directly related to systems. An example is a decision to increase the hull width to increase transverse stability. Note that such decision might be followed by system-related decisions, e.g. systems might be rearranged to make use of the new available space.

Figure 6 shows a schematic overview of the design rationale ontology. Note that the network representation is only a possible form of presenting the set of rationales. The top level represents a (digital) model of the concept design. The System Properties define the concept design, mainly describing "What" is designed. Interactions and Compromises principally describe "Why" the design is what it is. For each element, changes over time are traced (even if no rationale is expressed) to allow for a complete review of the design process.

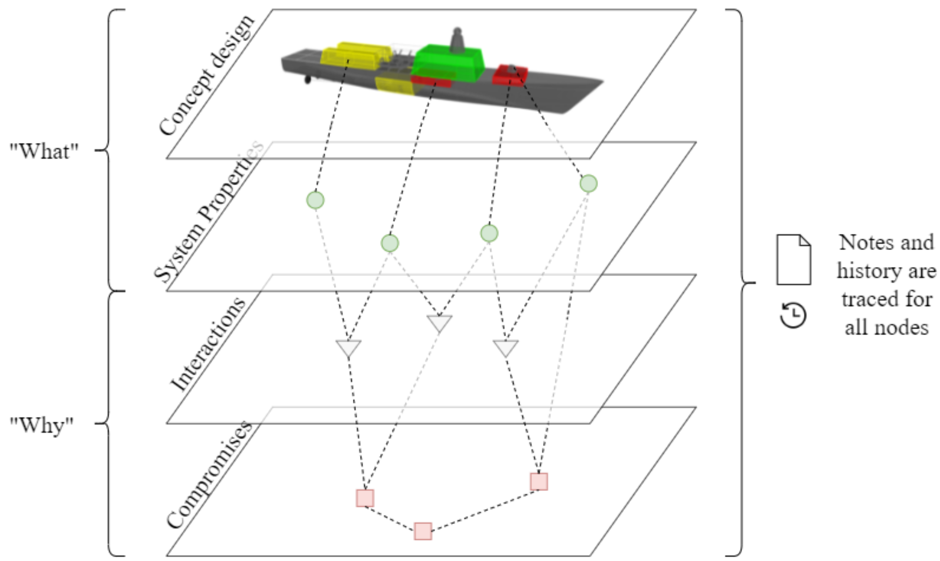

Figure 6: High level visualisation of the developed ontology to show the interrelationships between ontology elements.

To each category a *status*-element is added. This status element can be used to express confidence or satisfaction for each object in a category and its justification. The status can be set to:

1. *Agreed*, meaning: "At this moment, the current realisation of this object is satisfactory".
2. *Non-agreed*, meaning: "At this moment, the current realisation of this object is not satisfactory and to be improved".
3. *Pending*: the status has not yet been expressed. When some property of a rationale is changed (e.g. the position of a system), the status is automatically set to pending. Designers will need to express an explicit status for each element to ensure all design changes are eventually described.

Additionally, designers can express design rationale via a *design impact* indicator and its justification. Such indication can be used, for instance, to review the priority of design decisions when design changes are required. At the moment the following three design impact indicators are included:

1. *Global impact*, meaning: This design aspect (i.e. System Property, Interaction or Compromise) impacts the overall ship arrangement. An example is an engine room, which influences bulkhead positions, exhaust position, and topside arrays such as radars.
2. *Regional impact*, meaning: This design aspect impacts significant portions of the ship arrangements, e.g. the arrangement of systems within a zone or compartment.
3. *Local impact*, meaning: This design aspect impacts the ship's arrangement only locally. For instance, the internal arrangement of the galley dictates how the galley is shaped, which impacts the directly adjacent systems only.

The combination of status and design impact elements convey context-based priority of rationale elements. Such context is considered important to enhance the designers' ability to set coherent and meaningful priorities, in contrast to, for instance, numerical priorities. Such numerical values would need additional justification (Lehtola et al., 2004).

Besides the static description of “What” and “Why”, the ontology needs to include temporal relationships (RQ2). However, this is relatively easy as each design change and expressed design rationale can be given a timestamp when stored. No specific designer input is required here. Long term storage of design rationale can be achieved via various types of databases.

3.3 How to integrate the design rationale into the design process?

In contrast to the traditional design process presented in Section 2.3, this paper proposes to put a focus on design rationale in collaborative design decision-making. Indeed, the intended services also point to an integration of design decision-making and rationale reuse. For instance, captured design rationale (especially System Properties and Interactions) might be automatically evaluated in real-time to inform the ongoing design session.

Figure 7 shows the proposed design process, which comprises of the following activities:

1. **Generation**: Concept design generation will be partly preparatory to the design session. However, (semi-automated) concept generation tools will be used during the design session to generate concept designs in real-time to support the ongoing dialogue.
2. **Evaluation**: Like the traditional design session, designers evaluate the value of generated concept designs and propose changes, express preferences, etc. The in-session generation of concept designs enables real-time evaluation of the feasibility of these changes, see Section 2.2 and 3.1.
3. **Design rationale**: During the *Generation* and *Evaluation*, *Design rationale* is captured and stored in a database for future access. This design rationale can be retrieved to evaluate past decisions, used in the evaluation (e.g. MoPs), or in layout generation tools, as proposed in Section 3.1.

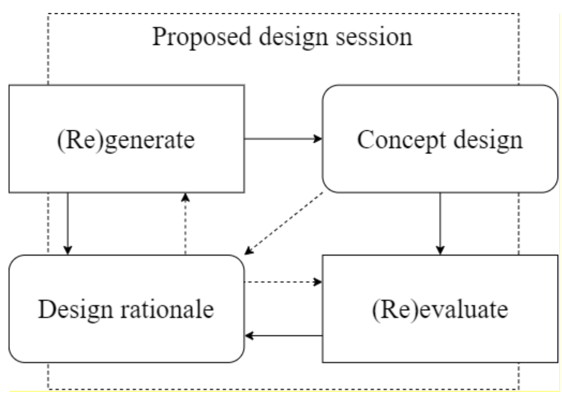

Figure 7: Representation of activities in the proposed design process, with focus on design rationale during design sessions

Although the proposed reuse of the captured design rationale does improve the relative benefits of using the methodology, it does not fully eliminate the need of manual input of rationales. However, an integration of design rationale and ship layout design tools would reduce manual work, since the “What” (i.e. the concept design and its underlying system properties) is typical data processed in design tools. Also, data coherency could be automated, reducing manual work.

4 CASE STUDY

To evaluate the usefulness of the developed design rationale methodology, a preliminary version of the methodology was used while arranging a notional Oceangoing Patrol Vessel (OPV).

4.1 Setup

The OPV concept design is based on the design assignment provided in an earlier MSc level design course lectured at Delft University of Technology. This assignment was originally completed in groups of three students. Although system selection based on (overambitious) mission statements was part of the assignment, the authors used a predefined list of systems based on student reports as a starting point of the exercise. An arbitrary hull size was taken as the starting point for the arrangement process. The end point of the exercise was considered to be the identification of the required descaling of the hull to reduce void space.

Since the design rationale methodology is not yet implemented in code, a 'sheet of paper' exercise is carried out for the purpose of this paper. Note that this limits the ability to evaluate the design guidance support service, presented in Section 3.1. The design rationale elements (System Properties, Interactions, and Compromises) are captured in Excel tables. An Excel and Rhinoceros-based design tool was used to visualise the concept design, as well as to calculate system areas and volumes. This design tool is loosely based on GCD2 (Takken, 2009) and precedes the design tools presented by Kana and Rotteveel (2018).

The case study is comprised of three steps:

1. *Capture prescribed rationales*. The design assignment prescribed System Properties, Interactions, as well as Compromises. System Properties comprise required sizing and global positions (e.g. *the floor of the cabins may not be situated more than 1 meter below the waterline*). An example of a prescribed Interaction is "*the RAS (Replenishment At Sea) stores need to be located in the vicinity of the RAS mast. Good logistics between the RAS mast and the stores is essential for smooth RAS operations with a reduced manning*". An example of a Compromise is the choice between "*the medical area should be horizontally adjacent to the flight deck for medical reasons*" and "*the medical area should be connected to the flight deck by an elevator*", see Figure 5.
2. *Concurrent arrangement of systems and capture of additional design rationale*. This step is comprised of two sub-steps:
    a. Capturing design rationale *prior* to arranging systems. When a system was considered, the designer considered possible global and relative positions and captured these. When the designer was convinced about the considerations, the system was arranged subsequently. The expression of design rationale was found to support thinking about the design options, similar to sketching (Pawling and Andrews, 2011).
    b. Capturing design rationale *after* arranging systems. This was done in cases where the preferred location of systems seemed constrained. Arranging systems first allowed a quick check whether the location was feasible.
3. *Analysis of developed design rationale network*. The design rationale network and concept design generated through the previous two steps were analysed to identify possible areas of attention for future research.

4.2 Results

Using the rationale ontology was found to be rather straight forward (RQ5). It allowed capturing of all rationales that were considered during the exercise. It also allowed easy reconsideration of earlier captured rationales (RQ2). The main challenge using the methodology was the lack of linkages in the data, which required extensive manual referencing between objects. Additionally, the design tool did not allow for tracing of changes of the concept design definition, although each generated design was saved individually. This limited the analysis of the development of Systems, except when System Properties were captured.

Table 2 summarises the growth of the network of captured Systems, System Properties, Interactions, and Compromises. The growth of the network indicates the importance of using useful ways to navigate and retrieve information from these networks. This is especially important to reduce the information overload and to enhance designers to show only the information that is important, e.g. for the stakeholder dialogue. Such information can comprise, for instance, only the nodes (e.g. system properties, interactions or compromises) related to a particular system or more detailed information for a specific node (e.g. the full justification, or the context of the decision). The full network might be considered when using network analysis tools, e.g. to identify the most important decisions.

Table 2: Design rationale network growth

Number of	Pre-arrangement	Post-arrangement
Systems	99	106
System Properties	11	43
Interactions	29	51
Compromises	3	9

Referring to RQ5, the integration of a design rationale methodology and design tools is required, to better capture the context of design decisions. Besides capturing design rationale inside the design tool, two concepts to visualise the captured design rationale in the context of the concept design were investigated:

1. Display the design rationale network, comprising System Properties, Interactions, and Compromises as layers over the concept design, see Figure 8. The visualization follows the ontology shown in Figure 6. This implementation led to the observation that the network might be hard to navigate. Although single-layer networks have been visualized over concept designs by others (e.g. Roth (2017)), the multi-layer ontology might be too complex for quick

comprehension. Another constraint is the relative limited information that can be expressed in node names without cluttering the network view.

2. These two constraints led to the proposal to visualise the design rationale network separately from the concept design, but with ‘data on demand’. This data encompass more elaborate information behind nodes, which can be highlighted by both navigating the concept design, as the network. The latter is visualised in Figure 9. This allows designers to see the network in a more effective way, compared to the visualization above, and retrieve detailed information when required. Yet, additional data filtering options need to be implemented to allow designers to efficiently navigate the network, e.g. to show only systems of interest. Figure 9 also includes a design timeline, communicating which rationales have been considered when. The vertical position of nodes in the network correspond to the timestamp at which that node was created. Due to limitations of the design tool, the timestamps of systems were not properly recorded, resulting in the assumption that all systems had been initialized from the start of the design session. This is considered reasonable, since most systems were indeed included in the initial list of systems.

   To illustrate the usefulness of status-elements, the most bottom-right compromise reads “Use frisc as buffer between accommodation and ER [Engine Room]. Does this suffice separation?”. In addition, the status of this compromise has been set to “Non-Agreed”, due to the check required.

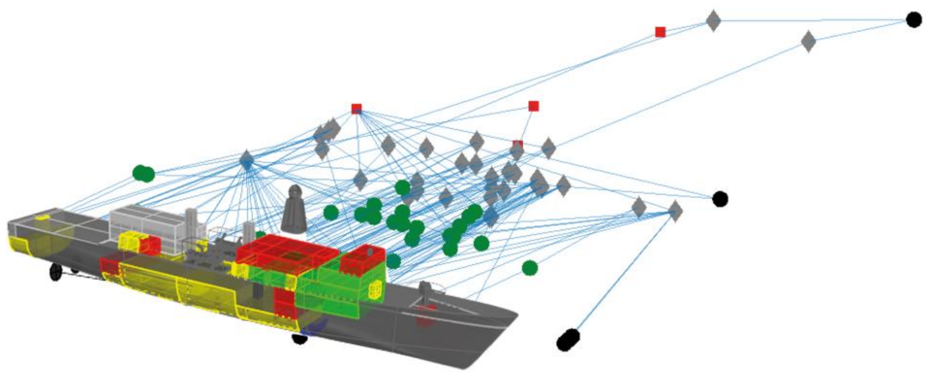

Figure 8: Rationale network overlaying concept design. System-nodes outside the concept design represent systems that have not yet been arranged. Node labels are disabled for clarity. Legend: Systems (black nodes), system properties (green nodes), interactions (grey diamonds), compromises (red squares).

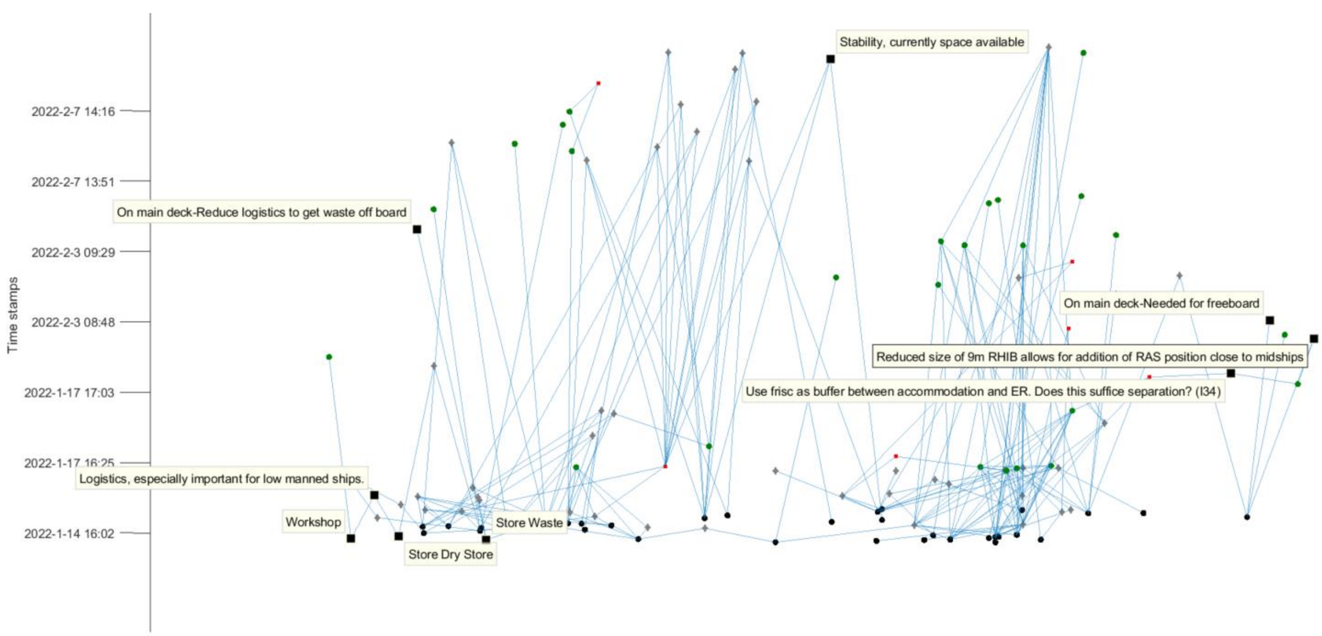

Figure 9: Data on demand – Node selection reveals detailed information on that node. Selected nodes are indicated by black squares. The vertical axis represents the design timeline. Note, the network shown is only a part of the network in Figure 8. Legend: Systems (black nodes), system properties (green nodes), interactions (grey diamonds), compromises (red squares).

During the case study the following three lessons learned for future work were identified:

1. Formalisation of interaction types is required. This would improve consistency of captured rationales and support the development of rationale-based design guidance.
2. The growth of the network and the high fidelity of the captured rationale, requires further investigation of 'data on demand'. The designers should be able to change perspectives on the captured data, e.g. ranging from an overview of the whole network to all details of a single rationale.
3. Trace design changes and automatically indicate whether these changes have been justified. This could support designers to add rationales at a late stage (e.g. after a collaborative design session) or allow for an evaluation of the design process.

Implementation of the full methodology is required to enable the application of the methodology in collaborative design sessions. Subsequently, the methodology can be fully evaluated.

5 CONCLUSION

This paper presented a proposal for a new design rationale methodology to support collaborative design decision-making during early stage complex ship design. The need to capture and reuse design rationales while the decision-making unfolds was identified as the most promising way to align stakeholders with the challenges of complex ship design.

A design rationale methodology was developed with the aim to provide designers the capability to capture and store design changes, as well as the reasons for these changes. This information might be retrieved at any point (e.g. during recursive design efforts) and used in the generation of metrics and tools that provide real-time design support to identify promising design directions.

A case study of a notional Oceangoing Patrol Vessel was presented. This case study was used to evaluate the usefulness of the developed rationale ontology and to identify challenges related to the retrieval of the design rationale. The need for a visualisation of the overall network of captured design rationale, as well as the retrieval of details of individual rationale elements, was identified to be important for effective reuse of captured rationales.

Although further implementation and testing of the methodology is required, the proposed design rationale methodology is expected to be a major step in providing designers an improved capability to capture and reuse design rationale during collaborative design decision-making.

DISCLAIMER AND DATA AVAILABILITY

The content of this paper is the personal opinion of the authors. Specifically, it does not represent any official policy of 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 the Defence Materiel Organisation.

The data underlying the case study can be found in the following repository: https://doi.org/10.4121/19430396. Due to confidentiality, source code of the tools used in this paper is not openly available. Access to the code may be granted for research and educational purposes. This is subject to written permission from the authors, the Delft University of Technology, and the Defence Materiel Organisation of the Netherlands Ministry of Defence.

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