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Development and experimental testing of a collaborative design rationale method for early-stage ship layout design

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A B S T R A C T

Design: rationale is a promising way of capturing design decisions and considerations for later retrieval and traceability to improve collaborative design decision-making. To achieve these perceived benefits for early-stage complex ship design, this paper first elaborates on the development of a proof-of-concept design rationale method. The method aims to aid ship designers in the continuous capturing and reuse of design rationale during the collaborative concept design process. Second, the setup and results of an experiment conducted with marine design students and with experts are discussed. This experiment shows how the developed design rationale method benefits collaborative design decision-making such that it leads to improved insight into design issues across the design team during a single design session.

1. Background

1.1. Challenges in ship design

The design activities undertaken for complex ships, such as frigates and heavy lift vessels, involve intertwined technical and social aspects. For instance, during a design meeting (i.e., social) an engineering problem (i.e., technical) can be solved (Minneman, 1991). Although interactions between designers and other stakeholders occur throughout the design process, the early design phase is crucial (Andrews, 2018b). In this early stage, the design problem is ill-defined, open-ended, and therefore lacks a definite right or wrong answer (DeNucci, 2012; Duchateau, 2016; Andrews, 2018a). Often, complex ships need to be designed for a wide range of potential missions and operations, contrary to transport vessels whose primary mission is more straightforward, namely to transport cargo or people from one place to another (Brown, 1986; Van Oers, 2011). Therefore, determining the required performance of complex vessels can be challenging, and thus determining what is actually wanted is the primary challenge during early-stage design (Andrews, 2018b).

Consequently, many stakeholders (including those with a non-engineering background) are involved in various aspects of the design (Brown, 1986; Van Oers et al., 2018). The task of the multidisciplinary design team during concept design is to generate concept designs, with the primary goal of understanding the complex relationship between the design and performance space (Duchateau, 2016). Eventually, such understanding is needed to understand and evaluate the technical and financial feasibility as well as risks associated with requirements (Andrews, 2018b; Van Oers et al., 2018). This information is used as part of a stakeholder dialogue to find out what is actually wanted, a process called ‘requirements elucidation’ (Andrews, 2003b, 2011; Kossiakoff et al., 2003). In such stakeholder dialogues, decisions on the requirements and the concept design are made - frequently leading to new design iterations to investigate the impact of those decisions on the integrated design. When the design process evolves, the attention shifts from understanding requirements to designing for production (Andrews, 1998). As such, the ship design process is a very human process with false paths and recursive design, and is impacted by factors inside (e.g., availability of information) and outside (e.g., legislation) that can disrupt the design process (Wolff, 2000; Andrews, 1981).

1.2. Multi-actor decision-making in ship design

During the concept design of complex and often innovative

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vessels, stakeholder involvement is essential to elucidating needs and requirements. However, stakeholder involvement is also needed to align the various specialists and design disciplines within the organisation (Van Oers et al., 2018; le Poole et al., 2022b). Since these specialists might have different design goals in mind, this process of alignment can help to create enrichment and negotiated knowledge to serve as a basis for decision-making with multiple actors (De Bruijn and Ten Heuvelhof, 2008; le Poole et al., 2022a, b).

Enrichment means that actors not only make compromises but also make a deal in which synergy between issues is created, leading to more value for all actors (De Bruijn and Ten Heuvelhof, 2008). For example, consider the following: in a ship design, two systems need to be separated for vulnerability reasons and adjacent for logistic reasons. A simple compromise would be to prefer one over the other. Enrichment takes place when actors exploit design options, such as blast bulkheads, to ensure vulnerability is not compromised while the systems are arranged close to each other.

Negotiated knowledge means that, on the one hand, the value of information in multi-actor decision-making networks is determined by the actors themselves and can be based on the perception of the ill-structured problem and the incentives or interests of actors (De Bruijn and Ten Heuvelhof, 2008). On the other hand, the role of experts is to provide actors with a state of objective knowledge. Indeed, not all information is negotiable, for example, an unstable ship remains unstable - regardless if one *wants* it to be stable. Experts, therefore, have a facilitating role in the generation of negotiated knowledge.

In design, knowledge frequently builds through the act of designing (Mavris and DeLaurentis, 2000; Andreasen et al., 2015). In other words, design knowledge is (partly) experimental or tacit knowledge (Nightingale, 2009). Such tacit knowledge can be hard to elucidate, but frequently is the basis on which design decisions are made (DeNucci, 2012). Because of the evolving nature of complex ship design, the outcome of the corresponding multi-actor decision-making processes cannot be determined beforehand. Similarly, the value of information (used to solve decision-making problems) can only be determined in hindsight (De Bruijn and Ten Heuvelhof, 2008).

Naval architects should devote “a lot of time and attention” to the accumulation of information relevant to their work (Watson, 1998). The goal of such information gathering is to use it in design problem-solving. As such, a naval architect is, on the one hand, an expert providing knowledge and expertise to enable the integration of systems in a coherent ship design, and on the other hand, naval architects are also actors within the process since they are responsible for or even leading this integration.

1.3. The role of design rationale

Another reason for the involvement of a wide range of specialists in the design process, besides the multi-domain complexity of ships, is to reduce the probability that the design team misses important design considerations (Fischer and Shipman, 2011). However, this requires that the reasoning behind design considerations and decisions (i.e., design rationale) is explicitly available (MacLean et al., 1991; Lee, 1997). Once design rationale is made explicit, it can improve communication and cooperation with other specialists and stakeholders (Wolff, 2000; Van Oers et al., 2018; Fischer and Shipman, 2011). Additionally, expressed design rationale makes tacit knowledge explicit and thus more tangible (Horner and Atwood, 2006; Fischer and Shipman, 2011). Such tangible knowledge is useful for long-term storage and training within organisations (DeNucci, 2012) and enhanced design documentation (Ball et al., 2001). Finally, being explicit about the rationale behind an idea can improve argumentation by triggering critical thought and reflection on that idea (Fischer and Shipman, 2011; McCall, 2010).

However, design rationale methods can be intrusive in the design process (Burge and Brown, 2000; Fischer et al., 1991) or can be not cost-effective when the designers bearing the costs are not the same as the benefiting persons (Lee, 1997; le Poole et al., 2022b). Designers can be reluctant to take the time to document the decisions they did not take or took and then were rejected (Conklin and Yakemovic, 1991). That is, they are less willing to spend time on ideas not considered valuable. However, the *reason* why these ideas are considered unimportant can be useful information at a later stage (e.g., rework of the design) (le Poole et al., 2022b). Also, designers can be hesitant to use a design rationale tool besides other design tools (Ball et al., 2001). With regard to the individual designer, capturing all design rationale is not possible (e.g., because decisions can be taken unconsciously based on tacit knowledge) and not desirable (design issues and their solutions can be obvious) (Ferguson, 1992; Fischer and Shipman, 2011). Ferguson (1992) states that to design layouts and calculations “dozens of small decisions and hundreds of tiny ones” are required. He continues that “too many inarticulate (and inarticulable) judgments” are involved to make all assumptions explicit.

While design rationale has been researched frequently in the fields of software design (e.g. Jarczyk et al., 1992; Aladib and Lee, 2019) and aerospace (e.g. Bracewell et al., 2009; Kuofie, 2010; Aurisicchio et al., 2016), the application of design rationale research in ship design has so far been limited. In practice, concept designs must often comply with pre-defined rules, such as classification society rules and international regulations. A lot of these rules lack the actual design rationale, i.e., although the rules reflect the implicit, underlying rationale of why that rule was needed and how it was developed, retrieving that rationale might be challenging (Derbanne, 2022). For example, a rule is that ships should have double lifeboat capacity, spread over the port side and starboard side. The implicit rationale is that if the ship capsizes to one side, still sufficient lifeboat capacity is available on the other side. As a result, often the explicit rationale behind concept designs can be missing.

In the past, design decisions and calculations were noted in a Book of Calculations, which was signed off when approving a ship design. Nowadays, computer programs and spreadsheets are used by designers to make calculations and generate designs (Andrews, 2021). Part of the rationale, therefore, is integrated into these tools. However, both assumptions and information sources should be noted (Andrews, 1986). Such rationale is to include the major design drivers, i.e. main design criteria with the largest size and cost impact (Duchateau, 2016). However, design documentation is typically done via reconstruction of the concept design, with the support of minutes of meetings, notes, and the designer's memory (le Poole et al., 2022b). Pawling (2007, p.120) states that such capturing of design rationale separately from design tools leads to a lack of the context of decisions. Thus, design rationale *is* being captured in ship design practice. However, 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).

In ship design, research into design rationale is limited. The primary example is DeNucci (2012), who developed a design rationale method to trigger individual designers to express and capture design rationale. Specifically, surprising and wrong concept designs were presented to designers to elucidate what designers did not like about the layout of these designs regarding global positions of systems and relative positions between systems (DeNucci, 2012). Although this proved to be an acceptable way to elucidate design rationale for ship layout design, reversing the logic will not automatically result in an acceptable concept design because:

1. Design rationale might, and is likely to, conflict, and thus, compromises need to be made (DeNucci, 2012).
2. The captured rationale can be situation or project dependent, and therefore the captured rationale might not be sufficient to make a fully informed trade-off.
3. These new concept designs might, in turn, trigger designers to express additional preferences which were not triggered by the original 'wrong' designs.
4. Time and budget availability are typically low during concept design, compared to detailed design phases (Andrews, 2018b), and therefore may be questioned whether designers are willing or able to spend time on expressing what's *not* wanted (Conklin and Yakemovic, 1991), before trying to implement the reverse logic in a feasible and balanced concept design.
5. Conflicting design aspects often require a dialogue between multiple stakeholders. DeNucci (2012) did not capture these resulting trade-offs.

After design rationale for ship design is captured, it may be utilised in various ways. For instance, existing concept designs can be evaluated for interrelations between systems (Roth, 2016; Sun, 2019; Pawling and Andrews, 2018). For example, the connectivity of specific systems can be compared across different designs (Pawling and Andrews, 2018). Similarly, network partitioning techniques can be used to automatically generate rough concept designs based on required global and relative positions of systems, and network metrics can be used to identify key systems (Gillespie, 2012). A network approach is also used to design distributed ship service systems for combatants (Habben Jansen, 2020; Duchateau et al., 2018) and submarines (Mukti et al., 2022). Furthermore, captured design rationale can be used by designers downstream of the design process to check whether past decisions are still valid.

Design rationale in the field of ship design can be distinguished at different levels throughout the iterative design process. During early design synthesis, the designer will make decisions (with corresponding design rationale) on aspects such as the overall style of the ship (including, for instance, decisions on the level of survivability, hull type, and propulsion concept) and generate concept designs comprising major building blocks (see for instance, Andrews (2003a); Van Oers (2011); Takken (2009)). Similarly, when the design is detailed further, decisions and rationale are more related to details, such as accurate arrangement and sizing of systems. Note that the evolvement of the concept design is not a goal in itself. For example, Baker (1956) used his “stylised design” (restricting the allocation of single functions to specific areas of the layout) to ensure that stakeholders beyond the designer were constrained from “interfering” in the design (Andrews, 2022b). However, further development and detailing of concept designs are often necessary. For instance, assumptions might need revision and a higher level of detail might be required to ensure technical feasibility and identify risks (Van Oers et al., 2018).

Although design rationale can be captured and reused, currently, there is no suitable design rationale method that considers the multi-actor decision-making aspect of complex ship design. Hence, the context of collaborative design decision-making needs to be explicitly considered when developing design rationale methods for ship design. None of the ship design examples mentioned above fulfilled this requirement. Thus, it's currently unknown how the potentially intrusive activity of design rationale capture can be effectively integrated into the multi-actor ship design process.

1.4. Proposed way forward

To address the aforementioned problem, the authors described how design rationale might be captured and reused on-the-fly during complex ship design (le Poole et al., 2022b). They found that being explicit about design considerations while designing enhanced the available justification behind concept designs. Furthermore, a design rationale method for collaborative early-stage ship design needs to comply with the following five requirements (le Poole et al., 2022b):

1. The method 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.
2. The method must enable the capture and review of design decisions, the rationale behind these decisions, and the temporal relationships between design decisions. That is, it must capture what is changed, how, why, and when.
3. The method 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 method.
4. The method must be generic. That is, it must be applicable for all ship types to allow for a broad and standardised application in ship design processes.
5. The method 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.

To achieve a sufficient cost-benefit balance for a design rationale method for early-stage complex ship design, the integration of design rationale capturing with immediate, short-term (e.g., during a design session) and long-term reuse (e.g., over the duration of a design project) is proposed.

Such an on-the-fly design rationale method would have multiple benefits. For example, it can be used to force actors to be explicit about design rationale and to retrieve justifications of design decisions (i.e. state of 0knowledge). Also, the availability of design justifications can help structure the decision-making process by reducing the need to reconsider the concept design (e.g., 'why did we do this in this way?'). In addition, being explicit about design considerations can improve the quality of the concept design.

The current paper describes the development of a proof-of-concept design rationale method as a proposal to the above requirements in Section 2. The objective of the method is *to aid designers in the continuous capturing and reuse* of design rationale during the collaborative concept design process. Such a method should support collaborative design decision-making by providing better insight into design issues. Furthermore, an experiment was conducted with maritime university students and experts in the field of complex ship design to *evaluate how the developed design rationale method benefits collaborative design decision-making such that it leads to better insight into design issues across the design team and to better concept designs during a single design session.*[1] The setup of the experiment is described in Section 3.

To evaluate the performance of the design rationale method, the

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[1] Evaluating the benefits of capturing design rationale over time is intended for future work.

following five questions related to various aspects of the experimental objective are answered:

1. *How is the method used by design teams over time?* That is, which functionalities are used when, and how does the use of the design rationale method influence the design process?
2. *How does the method support the negotiation process within design teams?* That is, how does the design rationale method provide better design insight during collaborative design decision-making?
3. *How does the use of the method impact the quality of concept designs?* That is, does the design rationale method also lead to measurable better concept designs?
4. *How does the use of the method impact satisfaction with the concept design across design teams?* If design insight, speed, or quality is improved by using the design rationale method, is this also perceived by individual participants?
5. *What are the perceived benefits of the method?* Besides the intended benefits, how do participants perceive the added value of the proof-of-concept design rationale method?

By investigating these aspects the qualitative and quantitative benefits of the proof-of-concept design rationale method are demonstrated in Section 4.

2. Method

This section describes the developed conceptual design rationale method, as well as its integration into a ship layout design tool. The method (and accompanying tool for the experiment) intend to aid designers in the continuous capturing and reuse of design rationale during the collaborative concept design process. To achieve this goal, the design rationale method is required to:

1. To allow designers to continuously work on the concept design since the development of the concept design is a primary objective for designers,
2. To support designers in capturing and storing relevant design rationale,
3. To enable designers to retrieve previously captured design rationale to inform the design decision-making process, and
4. To provide design rationale-based design feedback to inform the design decision-making process and to enhance the cost-benefit balance of the design rationale method.

Fig. 1 shows the architecture of the developed method. The left three elements (1, 3, and 9) represent the intended continuous design rationale capturing during the concept design process. The right four elements (5–8) are the new design rationale-based functionalities that the design rationale method offers to the designer to support the design process. Central are two connecting elements (2 and 4), where the design rationale method can identify design changes in real time and trigger the supportive functionalities to provide immediate feedback. The database servers as the long-term memory for the method. As such, the method stores design rationale and concept design changes and enables its retrieval.

In blue, the support of manual design changes and the identification of these design changes are shown (Section 2.1). Green elements are related to design rationale capturing and storage (Section 2.2). In orange, aspects related to design rationale retrieval and feedback are represented (Section 2.3).

2.1. Integration between design rationale and ship design tools

The design rationale method is intended to be used *during* design work, such that it supports design decision-making. Hence, the designer needs to be able to continuously design *and* capture design rationales. To reduce the intrusiveness of the design rationale method in the design process and enhance the ability for computer-based feedback to the designer, an integration between the design tool and the design rationale method is required.

One of the standard Computer-Aided Design (CAD) design tools used in ship design is Rhinoceros (McNeel, 2022), see for instance, (Takken, 2009; Van Oers et al., 2018; Kana and Rotteveel, 2018; le Poole et al., 2022b). Rhinoceros offers users various possibilities to develop compatible custom extensions using the visual scripting language add-on Grasshopper or Python-based scripting, for instance. Rhinoceros is chosen as the design tool for this research because it's already applied to ship design and offers the possibility to develop custom extensions (e.g., custom Graphical User Interfaces (GUIs)). The design rationale method was implemented in a custom-developed GUI, shown in Fig. 2. Through this GUI,

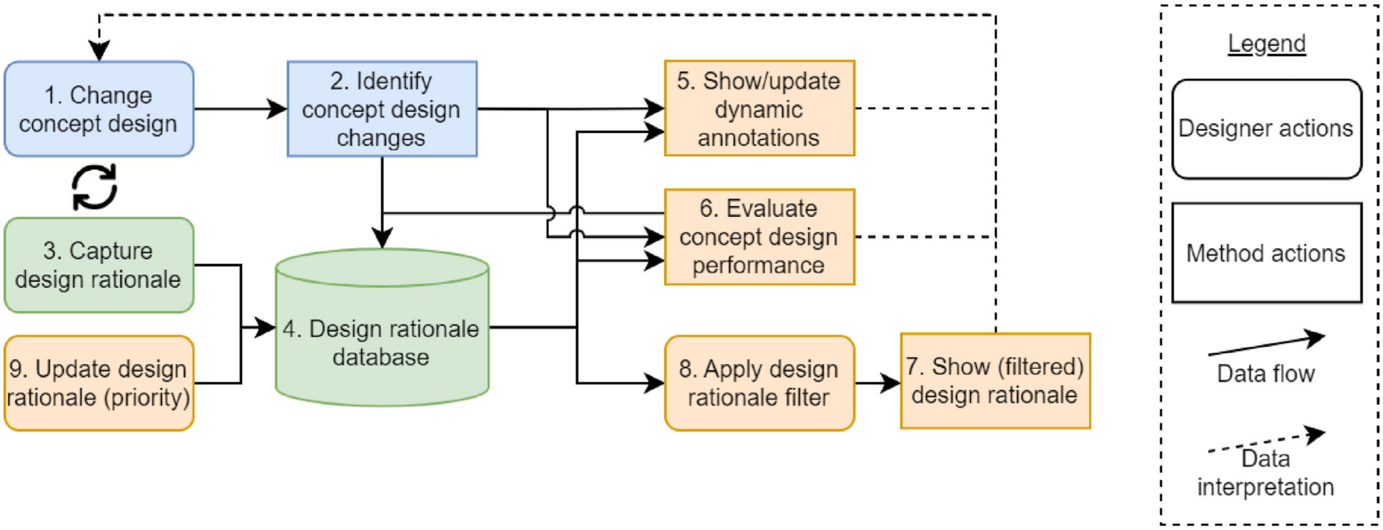
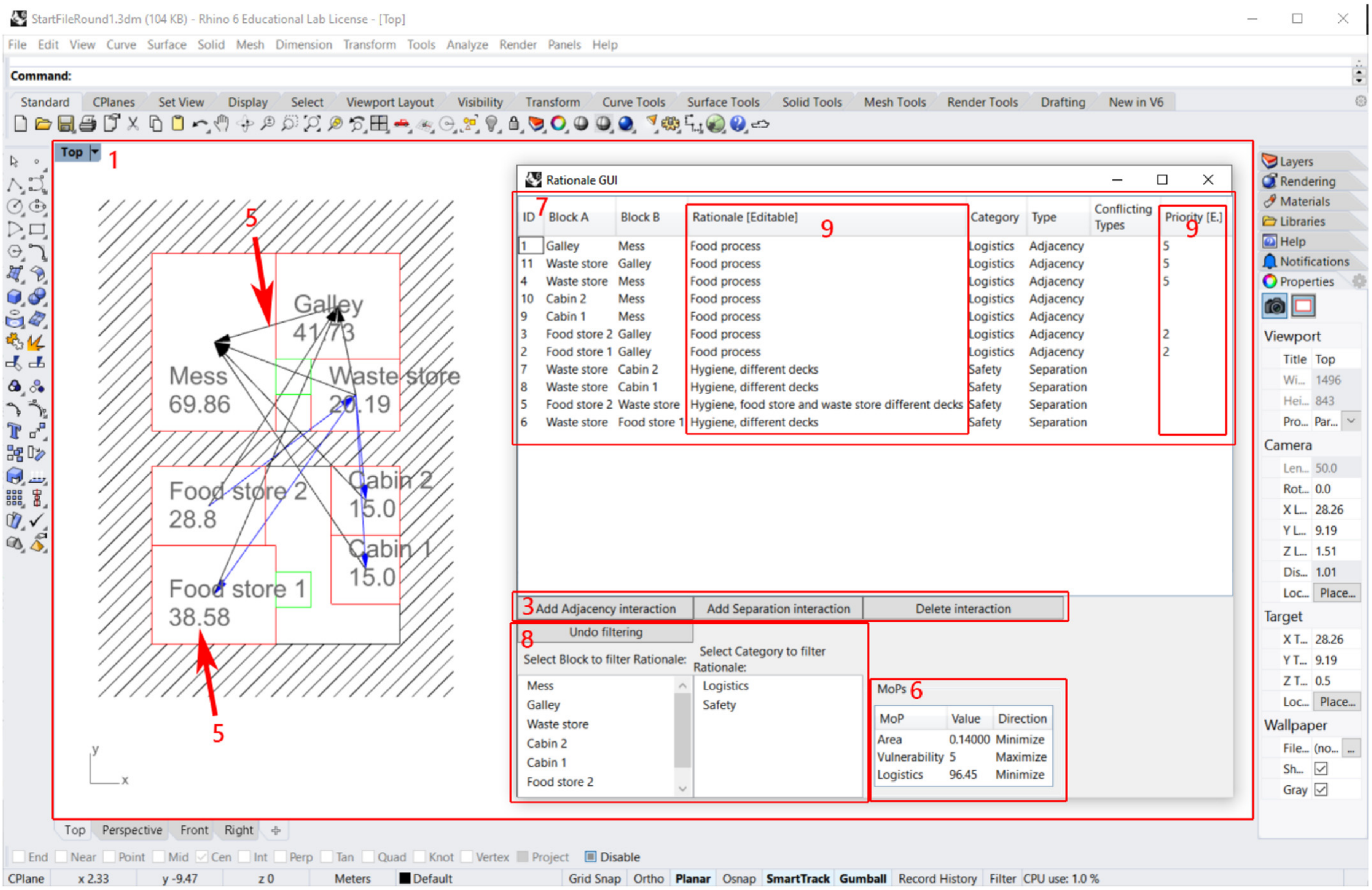


Fig. 1. Schematic overview of the developed method for ship layout design.



ID	Block A	Block B	Rationale [Editable]	Category	Type	Conflicting Types	Priority [E.]
1	Galley	Mess	Food process	Logistics	Adjacency		5
11	Waste store	Galley	Food process	Logistics	Adjacency		5
4	Waste store	Mess	Food process	Logistics	Adjacency		5
10	Cabin 2	Mess	Food process	Logistics	Adjacency		
9	Cabin 1	Mess	Food process	Logistics	Adjacency		
3	Food store 2	Galley	Food process	Logistics	Adjacency		2
2	Food store 1	Galley	Food process	Logistics	Adjacency		2
7	Waste store	Cabin 2	Hygiene, different decks	Safety	Separation		
8	Waste store	Cabin 1	Hygiene, different decks	Safety	Separation		
5	Food store 2	Waste store	Hygiene, food store and waste store different decks	Safety	Separation		
6	Waste store	Food store 1	Hygiene, different decks	Safety	Separation		

MoP	Value	Direction
Area	0.14000	Minimize
Vulnerability	5	Maximize
Logistics	96.45	Minimize

Fig. 2. Screenshot of design rationale method integrated into a Rhinoceros GUI. Numbers indicate steps in the method. Steps 2 and 4 are executed in the program's background.

designers can concurrently perform layout design work in Rhinoceros' main interface and use the design rationale method to capture and retrieve design rationale. The numbers in Fig. 2 correspond to the elements shown in Fig. 1.

The integrated design rationale method allows the designer to change the concept design (Step 1), while the method is able to identify which design changes are made and when (Step 2):

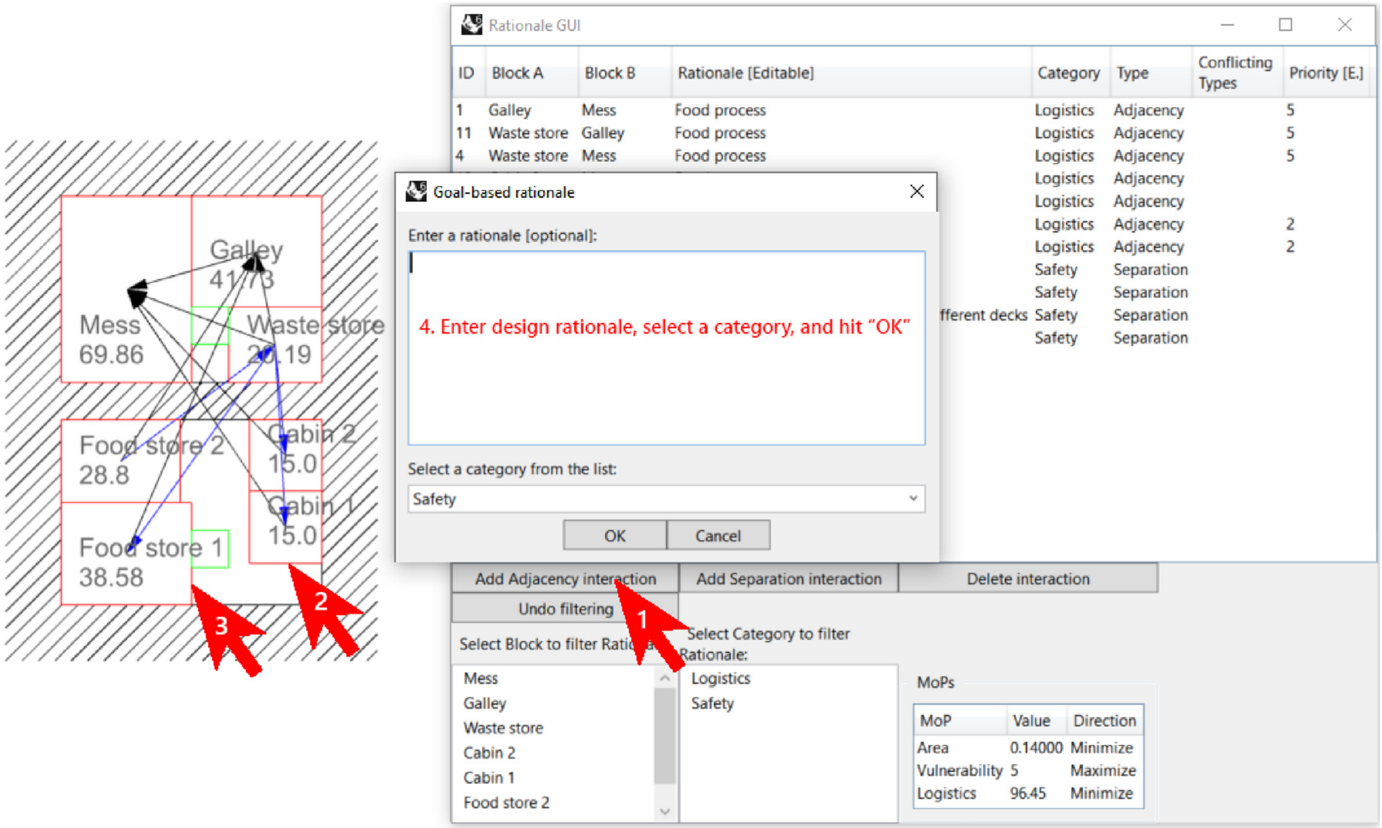
1. *Change concept design* (designer). The design rationale method is to support designers during design activities. Hence the designer needs to be able to change the concept design.
2. *Identify concept design changes* (method). The method needs to identify design changes for two reasons. First, to support computer-based design feedback. Implemented examples of such feedback are the design rationale-based Measures of Performance (MoPs) (Step 8) and the dynamic annotations feature of the design rationale feedback algorithm (Step 9), as elaborated in Section 2.3. Second, for research purposes, it is necessary to evaluate what has been changed to the concept design to relate these changes to the way the rationale method is used.

2.2. Capturing and storing design rationale

Before design rationale can be used, it needs to be captured (Step 3) and stored (Step 4) (DeNucci, 2012). Such capture and storage is especially important when automated computer-based design rationale support is required. Indeed, computers will not be able to provide such support if design rationale is not explicitly captured and adequately stored.

The design rationale capturing and storage steps are implemented as follows:

3. *Capture design rationale* (designer). Besides the integration of design tools and the design rationale method, the issue of intrusiveness is addressed in two ways:
   (a) A predefined design rationale structure based on an existing definition of interactions is used. An interaction is a preferred or required relation between two systems and its justification (DeNucci, 2012; le Poole et al., 2022b). An example of an interaction is: *the ammunition store should be adjacent to the gun* [relation] *to reduce the* dangerous transport of ammunition through the ship [justification] (le Poole et al., 2022b). By using a predefined design rationale structure, designers do not need to think about *how* to represent design rationale. This is especially important to ensure comprehensibility by both humans and computers (DeNucci, 2012). System Properties (e.g., preferred system position or sizing) have been hard-coded in the setup of the design problem and are used in Step 5.
   (b) Designers are allowed to select systems *in the layout* to define interactions. It was expected that this would be more intuitive than using drop-down menus, for instance, and thus reduce the effort required to capture design rationale. The designer action ‘capture rationale’ is illustrated in Fig. 3.
4. *Design rationale database* (method). All rationales and design changes are captured in a database for future reference. On the one hand, this allows the analysis of the design process, such as



ID	Block A	Block B	Rationale [Editable]	Category	Type	Conflicting Types	Priority [E.]
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11	Waste store	Galley	Food process	Logistics	Adjacency		5
4	Waste store	Mess	Food process	Logistics	Adjacency		5
				Logistics	Adjacency		
				Logistics	Adjacency		
				Logistics	Adjacency		2
				Logistics	Adjacency		2
				Safety	Separation		
				Safety	Separation		
			fferent decks	Safety	Separation		
				Safety	Separation		

Goal-based rationale

Enter a rationale [optional]:

4. Enter design rationale, select a category, and hit “OK”

Select a category from the list: Safety

MoPs

MoP	Value	Direction
Area	0.14000	Minimize
Vulnerability	5	Maximize
Logistics	96.45	Minimize

Fig. 3. Screenshot of rationale capturing action to capture an adjacency interaction between ‘Cabin 1’ and ‘Food store 1’. Step 1: select interaction type; Step 2 and 3: select corresponding systems in the layout; Step 4: complete design rationale. Subsequently, the captured rationale will be added to the database, and shown in the list in the main GUI.

shown in Section 4. On the other hand, this allows the designer to refer to past concept designs and supporting rationale, or to take a past concept design as the starting point for another design iteration. Besides storing design rationale, the database is also used to store design changes and the performance of concept designs.

It is important to note that the current version of the design rationale method is tailored to the experiment, which is elaborated in Section 3. Consequently, a fully operational design rationale method might need the implementation of additional or altered functionalities. For instance, currently, only a limited number of interaction types is included in the method, i.e., only adjacency and separation for multiple categories. In practice, one might want a more gradual distinction of the required relative distance between systems, e.g., should be separated; might be separated; might be adjacent; should be adjacent (see DeNucci (2012)).

2.3. Design rationale retrieval and feedback

Capturing design rationale has limited benefit when the design rationale is not used. Therefore, the method uses captured design rationale to provide visual feedback (Step 5) and evaluates the performance of the concept design, based on the current status of the concept design and captured design rationale (Step 6). Additionally, the designer can retrieve (Step 7), filter (Step 8), and update (Step 9) the captured design rationale when required. Steps 5 to 9 are further detailed below:

5. *Show/update dynamic annotations* (method). The method provides visual support to the designer by showing dynamic annotations overlaying the concept design. Examples of such annotations are arrows representing interactions between systems and textual annotations showing current system sizing. The position and orientation of such annotations are dynamically updated when the method identifies design changes (Step 2). Further, colouring is used to distinguish between, for instance, interaction types (e.g., adjacency and separation). Such annotations could be extended via additional context menus that open when an annotation is selected, for example.
6. *Evaluate concept design performance* (method): The method utilises the captured rationales (Step 3) in MoPs to inform designers off the quality of the concept design. For instance, design rationale related to logistics might be used in MoPs considering Manhattan distances between logistically connected systems (le Poole, 2018; le Poole et al., 2022b). To allow for real-time feedback, MoPs that require high computational efforts should be avoided unless such information is considered essential to make the right decisions.
7. *Show (filtered) design rationale* (method). An overview of captured rationales is provided to enable designers to review the design based on captured rationales. Since the number of rationales might be high, the designer might filter the rationale to view applicable rationales only. Also, the designer is informed on directly conflicting, i.e., contradictory, design rationales. For instance, when two systems are related by both adjacency and separation constraints.

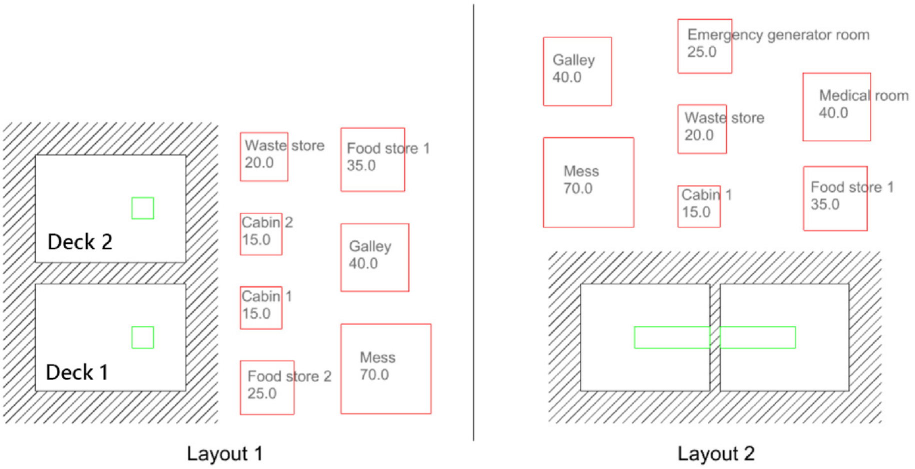

Fig. 4. Visualisation of the two layouts (black) and corresponding staircase or passageway (green) and systems (red). The numerical value in each system is its required area [m^2]. The current area of systems shown equals the required area. Compartments are sized 14 m by 10 m (Layout 1) and 12 m by 10 m (Layout 2).

8. *Apply design rationale filter* (designer). As explained above, the designer can decide which rationale is shown. Possible rationale filters are ‘system name’, ‘category’, ‘timestamp’ (i.e., date/time rationales are captured), and ‘systems in current view’ (i.e., only show rationales based on the zoom level and position of the design tool). In the current implementation, the filtering only applies to the interactions shown in the GUI and is based on the names of systems related to interactions and interaction categories. Additionally, the table with design rationale shown in the GUI can be sorted (i.e., by ascending or descending numerical or alphabetical value) by clicking the table headers.
9. *Change design rationale (priority)* (designer). In the GUI, each rationale can be given a priority indication. This can be used by the design team to capture initial trade-offs or varying preferences for interactions, for example. Also, the justification of each interaction can be altered to capture new design considerations. The updated design rationale is stored uniquely in the database.

3. Experimental setup

This Section elaborates on the experiment setup to evaluate the developed design rationale method. As elaborated in Section 1, the goal is to assess how this method benefits collaborative design decision-making, such that it leads 1) to better insight into design issues across the design team and 2) to better concept designs during a single design session. Note that this experiment is aimed to provide insight for the evaluation of the design rationale method, but is far from a real-world design scenario; see also Section 5.

3.1. Design problem

Design teams consisting of three participants were tasked with two small layout design problems, both containing two compartments and seven systems, see Fig. 4. The compartments in Layout 1 are arranged vertically adjacent and connected via a 2×2m staircase. The compartments in Layout 2 are arranged horizontally adjacent and connected via a 2 m-wide passageway.

3.2. Experiment setup

The task of each design team was to drag and scale all systems ‘manually’ into a sufficing layout. Each team member was assigned one of the following roles: ‘Naval Architect’, ‘Logistics Specialist’, or ‘Safety Specialist’. Typically, the Naval Architect in the team operated the tool, similar to real ship design processes. Team members were given a role sheet with requirements related to their specific roles. These requirements could be discussed, but the role sheets could not be shared among the team. The content of the role sheets is summarised in Table 1. These requirements comprise System Properties (i.e., required area) and Interactions (i.e., relative positions between systems).

The quality of each layout was captured via three MoPs based on System Properties and Interactions. The first MoP, AMoP is given in Eq. (1) (le Poole et al., 2019) and evaluates the sizing performance of the layout.

$$AMoP_i = \sum_j \max(0, (RA_j - AA_j)) \tag{1}$$

where:

system $j \in$ systems in layout i.
RA_j is the Required Area for system j.
AA_j is the Achieved Area for system j. If AA_j is larger than RA_j, no penalty or reward to the overall score is given. If systems overlap, the overlapping area is subtracted from AA for these systems.[2]

The second MoP, LMoP, is given in Eq. (2) and assesses the layout from a logistical point of view. It is based on the Manhattan distance between all pairs of logistically connected systems.

$$LMoP_i = \sum_k MD(k) \tag{2}$$

where:

$k \in$ Interactions related to Logistics in layout i.
MD is given by Eq. (3) and is the Manhattan Distance between two systems s and t in Interaction k.

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[2] This stimulates the development of layouts with rectangular-shaped systems (contrary to e.g., L-shaped systems).

Table 1
Role sheet information for each role in a design team.

Naval architect		Safety specialist			
System Name	Required area $[\mathrm{m}^2]$[a]	System Name A	System Name B	Interaction type[b]	**Rationale**
Mess	70	Galley	Mess	Adjacency	Hygiene
Galley	40	Food store(s)	Waste store	Separation	Hygiene
Food store 1	35	Cabin(s)	Waste store	Separation	Hygiene
Food store 2	25	Medical room	Waste store	Separation	Hygiene
Cabin 1	15	Medical room	Emergency generator room	Separation	Noise
Cabin 2	15	Emergency generator room	Cabin(s)	Separation	Noise
Waste store	20	Emergency generator room	Galley	Separation	Noise
Emergency generator room	25	Emergency generator room	Mess	Separation	Noise
Medical room	40				
Logistics specialist					
System Name A	System Name B	Interaction type[c]	**Rationale**		
Mess	Galley	Adjacency	Food process		
Galley	Food store(s)	Adjacency	Food process		
Mess	Cabin(s)	Adjacency	Food process		
Mess	Waste store	Adjacency	Food process		
Galley	Waste store	Adjacency	Food process		

[a] : Visually check realistic aspect ratios.
[b] : *Adjacency*: systems are in the same compartment. *Separation*: systems are in different compartments.
[c] : Adjacency is measured in Manhattan distance between systems. If spaces are in different compartments, the path includes the passageway or staircase.

$$MD(s,t) = \begin{cases} |x_s - x_t| + |y_s - y_t| & \text{if } s \text{ and } t \text{ in} \\ |x_s - x_{LSi}| + |y_s - y_{LSi}| + |x_{LSj} - x_t| & \text{if } s \text{ and } t \text{ in} \\ \quad +|y_{LSj} - y_t| + |x_{LSi} - x_{LSj}| & \\ \quad +|y_{LSi} - y_{LSj}| + |z_{LSi} - z_{LSj}| & \end{cases} \tag{3}$$

where:

(x_s, y_s) and (x_t, y_t) are the geometric centres of system s and t in compartment i respectively.
LS is a logistic system (i.e., a staircase or passageway) between compartments i and j.
$(x_{LSi}, y_{LSi}, z_{LSi})$ and $(x_{LSj}, y_{LSj}, z_{LSj})$ are the geometric centres of LS.

The third MoP, SMoP, is given in Eq. (4) and assesses the layout from a safety point of view. It captures how many safety related constraints are satisfied and unsatisfied in the layout.

$$SMoP_i = n(\text{satisfied } SI_i) - n(\text{unsatisfied } SI_i) \tag{4}$$

where:

SI_i is the set of Interactions related to Safety in layout i.
n is the cardinality of each subset (i.e. satisfied and unsatisfied).

To test the experimental setup, a preliminary version of the design problem and tool was provided to 12 Master's and PhD students. A main lesson learned was that providing MoPs to participants distracted them from directly considering the layouts. Instead, their attention was drawn to understanding and optimising the MoPs, in order to optimise the design. That is, design choices were principally made because the rough MoPs indicated that the layout would become better. This became apparent when one of the testing participants explicitly asked how one of the MoPs was calculated, “so that we would be better able to optimise the MoPs”. However, the MoPs are aimed to provide *guidance* in the design process and thus to support collaborative rational design decision-making on the design problems. For example, LMoP provides a measure of logistic performance but does not consider walking routes within compartments. Based on this observation, the decision was made to hide the MoPs during the experiment but use these to calculate in the background to allow for the analysis of the design processes.

Each experiment took 2 hours and was structured as follows:

1. Introduction to the research background and experiment by the paper's primary author (20 min).
2. Familiarisation exercise in teams (10 min). This exercise was designed to familiarise participants with the problem, Rhinoceros, and the design rationale method. If the experiment took place online, ‘break-out rooms’ were used in this and the two subsequent items.
3. Experimental round 1 in teams (30 min).
4. Experimental round 2 in teams (30 min).
5. Questionnaire, comprising 17 closed and 9 open questions (20 min). This questionnaire can be found in the Supplementary Materials and was aimed to elicit participant satisfaction with their teams' design process and resulting layouts, and to receive feedback on the design rationale method.

3.3. Evaluation

To evaluate the design rationale method, each team used a baseline method for one design problem and the design rationale method for the other design problem. The design rationale method is the method as presented in Section 2, with the exception of the hidden MoPs. The baseline method does not enable the capture and retrieval of design rationale, which also prevents the design rationale-based feedback. Hence, the baseline method forces teams to rely on verbal communication only. Using a baseline method besides the design rationale method allows for a comparison between the measured design quality and perceived satisfaction between the use of these two methods. Eventually, this comparison indicates the performance of the proof-of-concept design rationale method.

Two main learning effects have been identified during the setup of the experiment. First, participants could learn the nature of the presented design problems and they could approach the second design problem in a similar manner to the first design problem if that approach was found successful. The second learning effect is related to the order in which the baseline and the design rationale methods are used. The support that the design rationale method provides could stimulate participants to approach the second design problem in a different way compared to the situation where this aid was not provided. For example, the visual support of the dynamic annotations might trigger participants to consider the design problem from a network perspective. Although both learning effects need to be analysed to evaluate the performance of the design rationale method, only one learning effect could be studied due to the low number of participants. The second learning effect was selected because is considered to be the most significant since it is more related to the performance of the design rationale method. To elucidate the selected learning effect across the use of these methods, approximately half of the participants (Group A) used the baseline method first while the others (Group B) commenced with the design rationale method, see Section 3.4.

3.4. Participants

Participants of the experiment comprised TU Delft Marine Engineering Master and Ph.D. students (n = 15) and experts (n = 15) from the Materiel and IT Command (COMMIT), Netherlands Organisation for Applied Scientific Research (TNO), and DAMEN Naval, under informed consent. The experiment took place in five sessions between September 2021 and February 2022. The experiment protocol was approved by the TU Delft Human Research Ethics Committee.

Recruitment for student participation was done via a course taught by the three authors affiliated with TU Delft. This was done via online announcements in the digital student learning environment Brightspace and email, as well as in-class announcements. Furthermore, students were recruited from the research lab of the fourth author. Recruitment for expert participation took place via the professional network of the authors.

Participants were subdivided into teams of three persons. Each team comprised persons with the same affiliation. Each team was assigned to Group A or B. Teams in Group A used the baseline method in the first experimental round, while teams in Group B commenced with the design rationale method. Table 2 shows the distribution of participants over teams and groups.

Due to COVID-19-related restrictions, two teams performed the experiment via an online environment. All teams participated either entirely in-person or entirely online. No mixed in-person/online teams took part. The effect of online versus offline participation is not studied.

Four participants from the test run in August 2021 did participate in an online session in January 2022. Hence, these participants were more familiar with the design rationale method and a general idea of the design problem provided during the experiment. One team was entirely composed of participants who had been involved in testing, although in other testing teams. This group was not excluded from analysis, because: 1) the baseline method was not tested by these participants, 2) the design problem was changed substantially, and 3) the limited availability of other, non-biased participants.

4. Results

This section elaborates on the qualitative and quantitative results obtained from the experiment to evaluate how the developed design rationale method benefits collaborative design decision-making such that it leads to better insight into design issues across the design team and to better concept designs during a single design session. The qualitative and quantitative data are retrieved from logged data by the methods and a post-experiment questionnaire. The data analysis is structured by the questions posed in Section 1:

1. Section 4.1 answers: ‘How is the method used by design teams over time?’
2. Section 4.2 answers: ‘How does the method support the negotiation process within design teams?’
3. Section 4.3 answers: ‘How does the use of the method impact the quality of concept designs?’
4. Section 4.4 answers: ‘How does the use of the method impact satisfaction with the concept design across design teams?’
5. Section 4.5 answers: ‘What are the perceived benefits of the method?’

4.1. Use of the design rationale method

The design rationale method adds new activities to the design process (e.g., capturing of design rationale and setting of priorities). Furthermore, the visual feedback (i.e., arrows representing interactions and the overview of captured rationales in the GUI) is

Table 2
Summary of participants.

	Group A		Group B			
	Participants	**Teams**	**Participants**	**Teams**	Total Participant	Total Teams
Experts	5[a] [0]	2 (0)	9 [0]	3 (0)	15	5
Students	13 [1]	4 (1)	3 [3]	1 (1)	15	5
Total participants	18		12			
Total teams		6		4		

[a] : To complete an expert team, the first author (student) participated in one team. (n): number of teams online. [m]: number of participants in test run.

expected to enhance the participants' overview of the design problem. In contrast, the added functionalities take time and effort. In this section, the use of the design rationale method in the arrangement process is investigated based on tracked designer actions.

First, the use of design rationale method functionalities over time is investigated to identify which functionalities are used when in the process. As the baseline method does not offer functionalities related to design rationale, only the use of the design rationale method was investigated. The following actions could be performed using the design rationale method:

1 *Open*: The design rationale GUI was opened. This happens at the start of the design process or after the tool crashes. The latter occurred relatively often during the earlier experiments.
2 *Close*: The design rationale GUI was closed.
3 *Add rationale*: The team added an interaction using the design rationale method.
4 *Delete rationale*: An interaction was removed, e.g., because the team selected the wrong interaction type.
4 *Rationale edit*: The priority or justification of an interaction was changed.
6 *Filtering*: The team used one of the filtering options in the GUI to retrieve a selection of captured design rationale.

Unfortunately, not all actions were traced for all teams. For instance, traceability of the filtering action was only implemented after Team 7 performed the experiment. This significantly limits the analysis of the use of functionalities and only enables some rough observations based on the design processes of Teams 8–10. In the remainder of the paper, the data of all teams is used in the analysis, with one exception. Team 1 needed to restart after the tool had crashed completely. Hence the quantitative data from Team 1 is not considered reliable for the analysis of the design process. Team 1's answers to the questionnaire results are used, however.

Fig. 5 shows which actions were used by Teams 8–10 in the design rationale method as well as when these teams arranged systems. Teams 8 and 10 worked on the first design problem, while Team 9 worked on the second one. In all cases, design rationale was captured in the first half of the experimental round. Team 9 also captured design rationale after completing the experiment. The large red 'Close' bar indicates that Team 9 waited for approximately 8 min to close the GUI after conducting the last action in the GUI. Table 3 provides the average use of each action across the three teams. The 'Close' action is not considered in the data to remove the excess waiting before closing the GUI. Approximately 55% of the experimental round was spent on the actual arrangement of systems, while 22% was used on design rationale capture. The possibility to filter design rationale in the GUI was used relatively often as well (10%). There was only minimal deletion of design rationale. Typically, design rationale was only deleted when an error was made upon rationale addition.

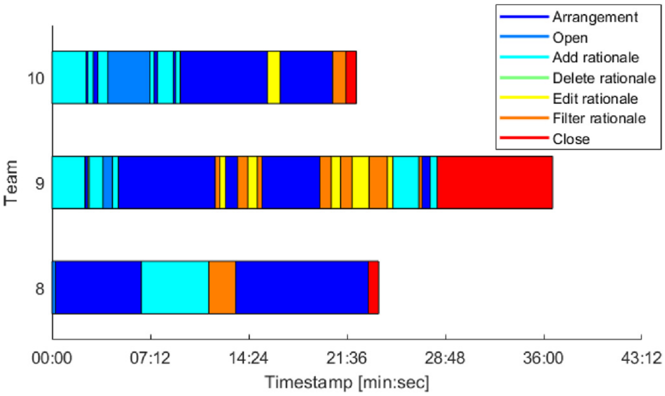

Fig. 5. Use of the design rationale method over time by Teams 8–10.

Second, the process of arranging systems is further investigated to evaluate whether the design rationale method triggers designers to approach design problems differently (e.g., to consider the whole design problem upfront contrary to considering large systems first), i.e., the second learning effect identified in Section 3.3. An initial analysis of the development of concept designs over time showed that teams differed with respect to *when* they did *what* modifications to systems, e.g., resizing and moving. To further investigate this observation, the following six types of system modifications are defined:

1. *Resize outside*: a system is resized outside a compartment.
2. *Resize inside*: a system is resized inside a compartment.
3. *Move outside*: a system is repositioned outside a compartment.
4. *Move inside*: a system is repositioned inside a compartment.
5. *Move cross*: a system is repositioned across a compartment boundary, either from outside to inside the compartment or vice versa.
6. *Move cross-compartment*: a system is repositioned from one compartment to another.

A visual explanation of these six system modifications is provided in Fig. 6.

Additionally, the design timeline is divided into five phases with equal duration. Since each round lasted for around 30 min, each phase corresponds to approximately 6 min. It is expected that different system modifications are applied in different phases. For example, towards the end of a round, most major decisions on system positioning have likely been made, and most actions are related to fitting all systems into the layout (i.e., modifications 'move inside' and 'resize inside' are expected to dominate).

All system modifications captured during the experiment are categorised to the type of modification and design phase. Also, a differentiation between experimental rounds 1 and 2 and between using the baseline or design rationale method is made. Subsequently, the contribution of each modification in each phase is calculated using Eq. (5).

Table 3
Average use of actions in the design rationale method for Teams 8–10, as percentage of each team's experimental round duration.

	Arrangement	**Open**	Add rationale	Delete rationale	Edit rationale	Filter rationale
Team 8	69.1%	1.1%	21.3%	–	–	8.5%
Team 9	46.1%	2.5%	22.2%	0.4%	12.2%	16.6%
Team 10	51.6%	14.3%	25.2%	–	4.3%	4.5%
Mean	55.6%	5.9%	22.9%	0.4%	5.5%	9.9%
Standard deviation	12.0%	7.3%	2.0%	0.0%	5.6%	6.1%

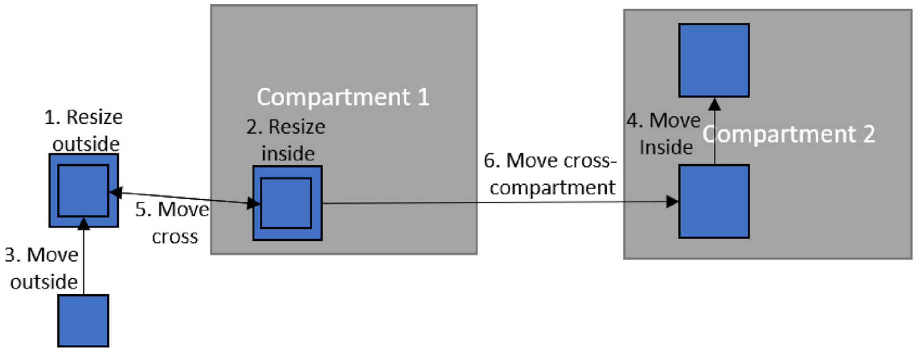

Fig. 6. Visual explanation of the six types of modifications to systems.

$$contribution_{i,j,k} = \frac{\sum_k \frac{\text{number of modifications}_{i,j}}{\text{total number of modifications for } k}}{n} \tag{5}$$

where:

$i \in$ Phases.
$j \in$ types of modifications.
$k \in n$ teams in the same experimental round and group.

The results are shown in Fig. 7. The following observations can be made:

1. The modifications '*move inside*' and '*resize inside*' were dominant in later design phases. This holds for both different design problems and different methods. This corresponds with the expectation above.
2. The modification '*resize inside*' was used significantly more than other types of modifications. This might be explained by the observations 1) that the last design changes were primarily performed to make the layout fit, 2) that moving a system in the correct position was easier than modifying its size into the proper shape, and 3) that resizing was used to reposition systems, i.e., by extending the length of a system, it can be connected to an adjacent system.
3. For Group B, the modification '*move outside*' was very dominant in Phase 1 when using the baseline method, as well as in Phases 1–3 when using the design rationale method. For Layout 1, Group B used the design rationale method and generally spent one or two phases on capturing design rationale. Then, these teams used the systems and annotations to roughly figure out which layout was preferred, before commencing with the detailed arrangement of systems in compartments. This way of utilising the layout to perform initial major decision-making will be called '*network arrangement*'. An example is shown in Fig. 8. For Layout 2, Group B used the baseline method. Hence, no time was required to capture design rationale. Consequently, network arrangement (although without interaction annotations) commenced already in Phase 1.
   A similar trend, although less clear, can be seen when comparing the '*move outside*' modification using the baseline and design rationale method for Group A. A slight increase of modification '*move outside*' can be observed from Layout 1 to Layout 2, i.e., from baseline to design rationale method, in the first three Phases.
   Based on these observations, it is expected that the dynamic annotations provided by the design rationale method and the

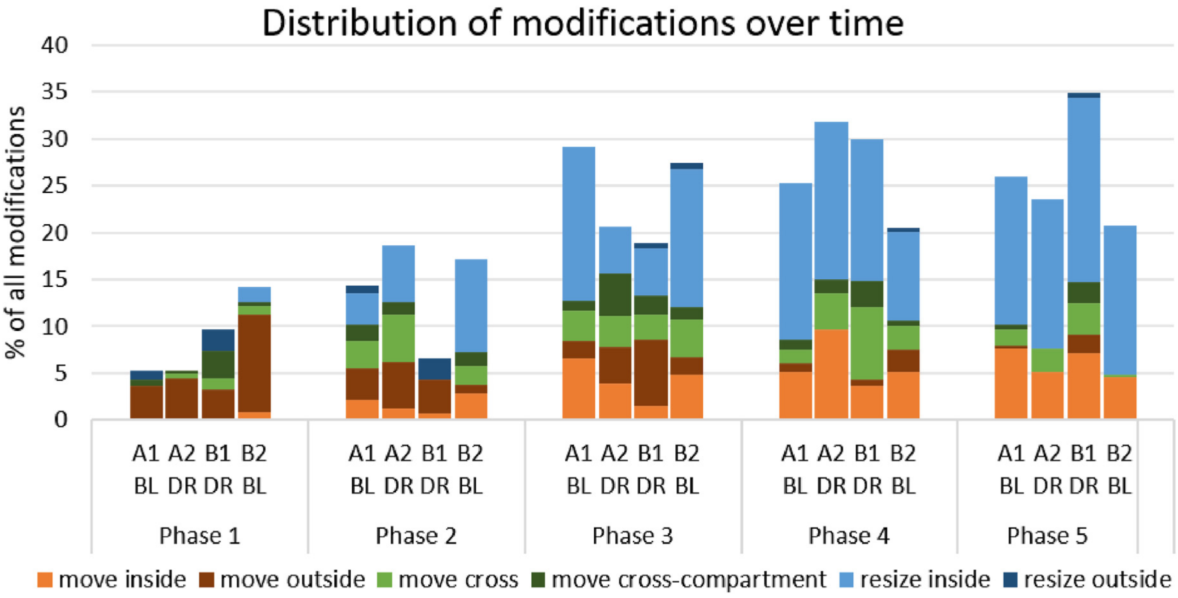

Fig. 7. Distribution of modifications over time. A1: Group A, Layout 1. A2: Group A, Layout 2, etc. BL: baseline method. DR: design rationale method.

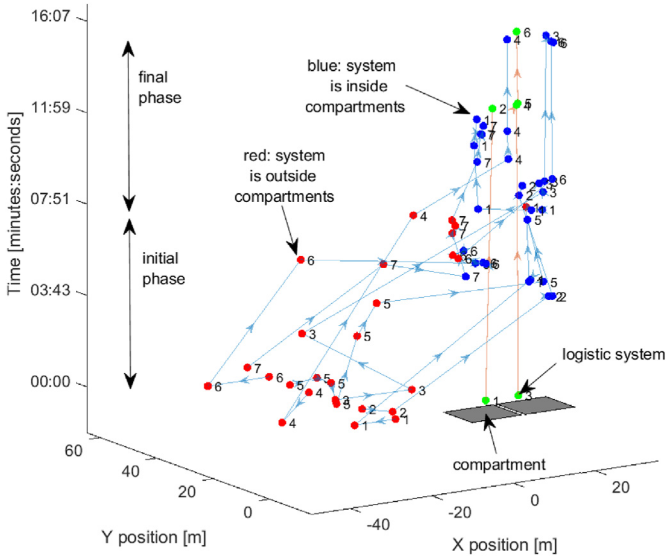

Fig. 8. Network arrangement (initial phase) and detailed arrangement (final phase) demonstrated by Team 9, Layout 2. The graph shows the X,Y position of (logistic) systems over time. Each node represents a modification to the corresponding system. Note that the initial network arrangement was adapted during detailed arrangement: system 6 (Medical room) was moved to the right compartment, and systems 1 (Mess) and 7 (Emergency generator room) were moved to the left compartment.

need to be explicit about all design rationale upfront can trigger teams to first arrange systems roughly based on required interactions and area, and then arrange systems in detail. In other words, the teams seem to ‘sketch’ to support the negotiation process. Sketching is an important means of conveying design thinking but is hardly supported by today's ship design tools (Pawling and Andrews, 2011).

4. The modifications ‘*move cross*’ and ‘*move cross-compartment*’ were used relatively more when using the design rationale method, compared to when using the baseline method. Also, these modifications were mainly observed in later phases. This might indicate that the outcome of the initial decision-making using ‘*move outside*’ modifications, as described in point 3, turned out to be infeasible when systems were actually arranged in the layout. Another explanation might be that completely other arrangements were investigated in later phases. Such investigation could be performed because, for instance, a specialist was not satisfied with the initial arrangement (which now had become more tangible than in the network representation) and wanted to improve the layout or because the team did already identify multiple possible allocations of systems to compartments during the initial phases.

Despite the limited data logging, the results in this section indicate that all options in the design rationale method have been used. Furthermore, the results indicate that the design rationale method triggers teams to ‘sketch’ more often to support the negotiation and design process compared to the baseline method.

4.2. Support of the negotiation process

The design problems were deliberately created to contain conflicts, i.e., trade-offs where necessary. Hence, each team needed to negotiate to resolve these conflicts. This section focuses on the perceived support provided by the design rationale method in the design process.

To elucidate participants’ perception of the supporting role, the post-experiment questionnaire contained six statements regarding this topic. The responses to these statements are presented in Fig. 9. Generally, the design rationale method was perceived to support the decision-making process (80%) and was not distracting for most participants (54%) but was distracting for some participants (18%).

A key intended benefit of the design rationale method is providing an overview of relevant design considerations. Therefore, statements 2, 4, and 5 concern this aspect. Most participants indicated to (strongly) agree with these statements, respectively 86%, 82%, and 93%.

On average, 26% of the design sessions using the design rationale method was spent on rationale capturing, while the remainder was used to arrange the systems. The time spent on design rationale is a part of the effort required to apply design rationale during design. Still, 82% of the participants indicated that the gains outweigh the (temporal) costs of using the method.

Participants were also requested to describe how the design rationale method supported decision-making compared to the baseline method. The following statements are a representative selection of answers to this question:

> “*The DR method helped better to understand the interactions between the spaces.*”
>
> “*Better alignment of rationale and a more explicit discussion.*”
>
> “*It centralised the discussion.*”
>
> “*The baseline method resulted in ‘chaos’ and repetition in discussions.*”
>
> “*Explicit visualisation of each other’s rationale helps [to] optimise together.*[3] *Even [the safety specialist] was looking at logistics and vice-versa* …”
>
> “*Forces a baseline of knowledge for [the] whole team.*”

These quotes and the responses to the closed questions indicate that the design rationale method supports the negotiation process by facilitating enrichment and negotiated knowledge and is perceived to provide a better understanding of the design problem within design teams.

4.3. Quality of concept designs

Since one part of the goal of the design rationale method is to improve the quality of design, the quality of the developed concept designs is investigated. The MoPs for each design discipline are used to measure the quality of each concept design.

4.3.1. Quality through MoPs

First, the quality of all final concept designs is compared. Fig. 10 shows the three MoP scores for each final design of each team. For design problem 1, the final designs are concentrated along the LMoP axis. This means that these designs meet the required area requirements for all systems. Satisfying all area constraints is relatively easy in this design problem since the total available area is 280m^2, while the total required area for placing all blocks (without considering logical placement) is 220m^2. Nonetheless, Teams 3 and 7 failed to meet the required area constraints. An investigation of the associated final layouts of these teams showed that the mismatch between the required and achieved areas could

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[3] Optimisation here refers to making decisions based on perceived merit and objective numbers, such as system sizing.

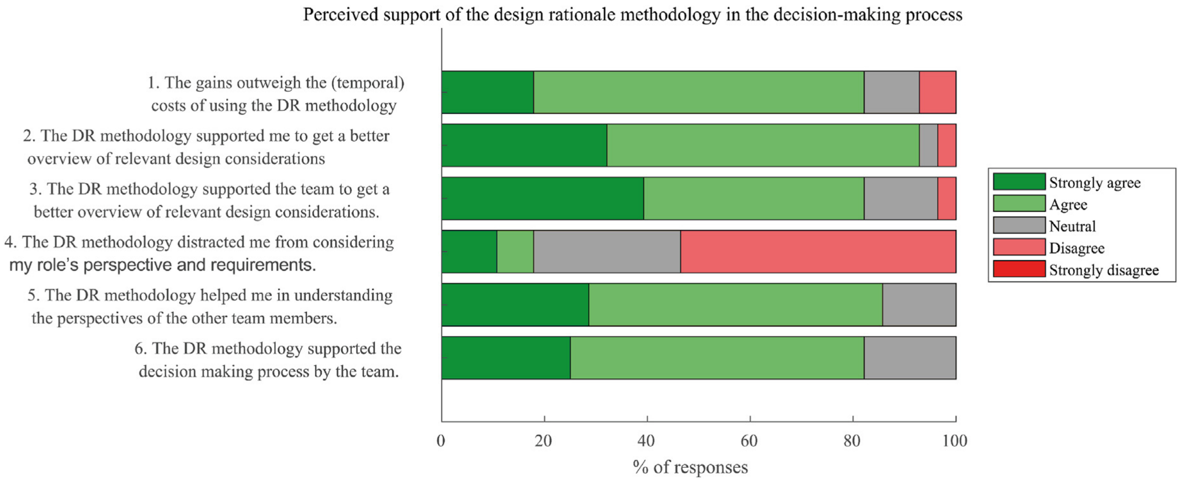
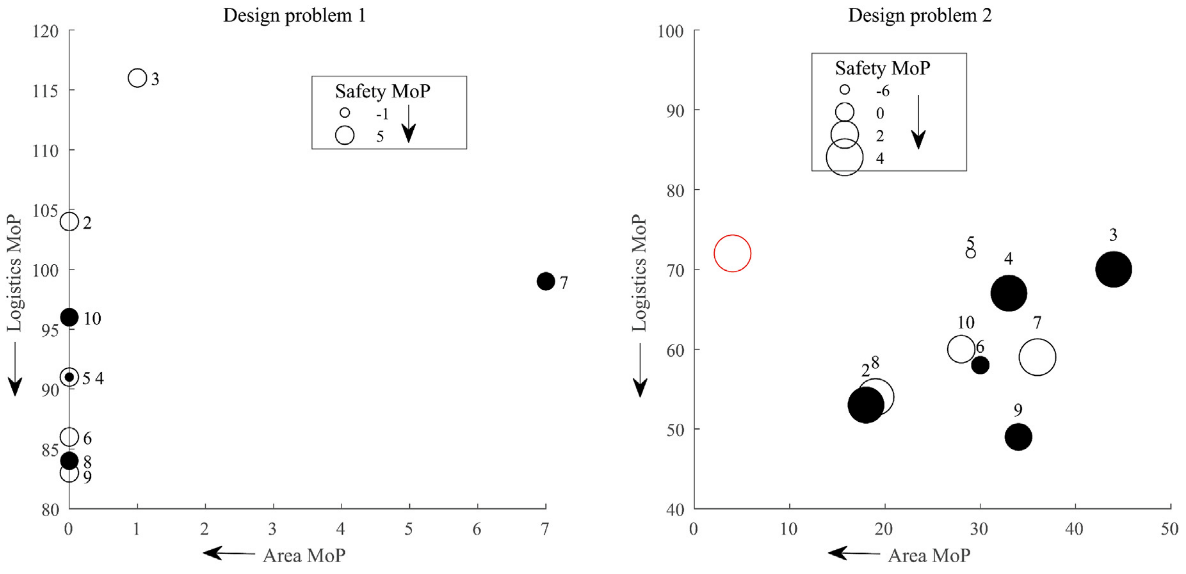


Fig. 9. Perceived support of design rationale method in the decision-making process (n = 28).



(a) Design problem 1

(b) Design problem 2

Fig. 10. MoP scores for the final designs of all teams for both design problems. Open nodes: baseline method; filled nodes: design rationale method; arrows point in favourable direction. Red: scores for Team 5 when accounted for leaving out the Emergency Generator Room. Team 6 and 7 were online.

be resolved. An explanation could be that, due to time limitations, teams did not put the ‘finishing touch’ to the layout. Most teams maximised the safety MoP, although Team 5 violated relatively many safety constraints (SMoP = -1). The results indicate an even spread in layout performance between teams using the baseline and the design rationale method.

For design problem 2, the final designs are spread across all three MoPs. Four teams used the baseline method, and six teams used the design rationale method for this design problem. Meeting all required area constraints is impossible for this design problem, since the total available area is $240m^2$, while the total required area is $245m^2$. With regard to safety constraints, one team satisfied four (SMoP = 0), two teams met five (SMoP = 2), and five teams met six (SMoP = 4) safety constraints. One team (Team 5) met only two safety constraints of eight safety constraints (SMoP = -6). Although this is not apparent from Fig. 10(b), Team 5 decided to arrange the Emergency Generator Room (EGR) at another notional deck to solve the shortage of available area, see Fig. 11(d), thereby not adhering to the given constraints of the design problem. If this decision satisfies the required area of the EGR and interactions with other systems, this team scores AMoP = 4, SMoP = 2, while LMoP stays 55 and shifts to the Pareto front. This is shown as a red node in Fig. 10(b). Again, there seems to be an even spread in layout performance between teams using the baseline and the design rationale method.

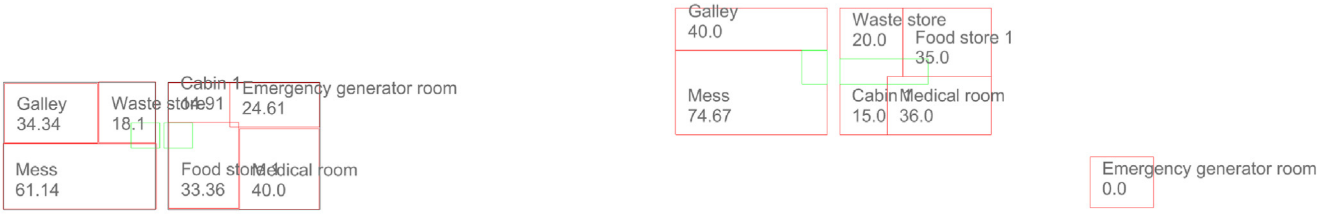
Teams 6 and 7 participated in an online session. All other teams completed the experiment in person. Scoring worst in the first round, Team 7 achieved an average score in the second round. Team 6 achieved a good performance in the first round and also achieved an average score in the second round. Therefore, online participation gives similar results compared to in-person participation in the experiment.

4.3.2. Visual comparison

Second, a subset of the final concept designs is compared. For design problem 1, the final designs of Teams 4 and 5 are compared because these scored similar with respect to AMoP and LMoP but

(a) Design problem 1: final layout generated by Team 4.

(b) Design problem 1: final layout generated by Team 5.



(c) Design problem 2: final layout generated by Team 2.

(d) Design problem 2: final layout generated by Team 5. The team decided to arrange the Emergency Generator Room at another deck to have sufficient available area for the remaining systems.

(e) Design problem 2: final layout generated by Team 8.

(f) Design problem 2: final layout generated by Team 9.

Fig. 11. Six of the twenty final layouts generated during the experiment.

achieved a different SMoP. For design problem 2, the designs on the first two Pareto fronts (in the Logistic-Area plane) were compared.

4.3.2.1. Design problem 1: teams 4 and 5. The final layouts of these teams are shown in Fig. 11(a) and (b), respectively. As said, these layouts scored the same score for AMoP and LMoP but had a different SMoP. For the Safety Specialist the main consideration is in which compartment systems are arranged. From that perspective, the two layouts are very similar, despite being mirrored. The main difference is the location of the Waste Store and Food Store 2. Based on the prescribed interactions, Team 4 made a better trade-off from an SMoP perspective. However, Team 5 seems to have preferred reduced logistical movement in the food preparation process by locating a Food Store close to the Galley. It is noteworthy that Team 5 did use the design rationale method for this design problem.

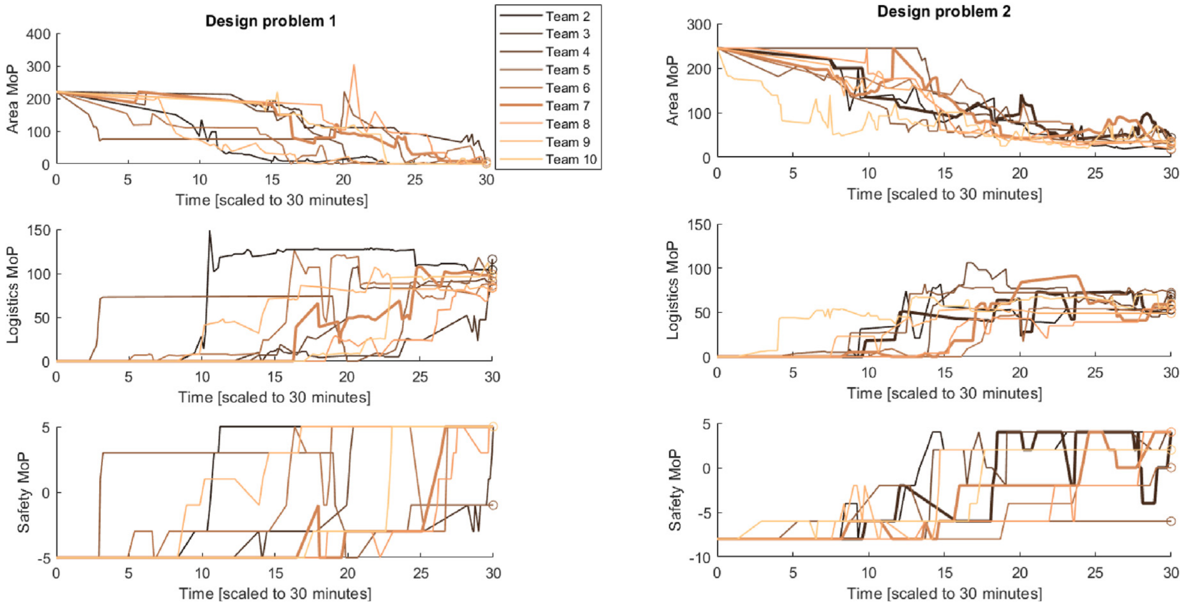
4.3.2.2. Design problem 2: teams 2, 8, and 9. From a safety perspective, Teams 2 and 8 created the same design. Team 9 made a different trade-off in five of eight safety-related constraints. For instance, Team 9 decided to separate the Galley and Mess. Also, Team 9 differentiated from Teams 2 and 8 because it kept the default passageway size. As a result, less area was available to arrange systems, which is reflected in the higher AMoP (34, compared to 18 and 19 for Teams 2 and 8, respectively). Although the layouts are somewhat mirrored, the difference between the LMoP for Teams 2 and 8 is small (53 and 54, respectively). Team 9 achieved a better LMoP, scoring 49. The team also expressed five additional interactions after the arrangement was finished, which explain some of the design rationales behind the layout:

1. Galley and Food Store 1 are adjacent: *“Access to the Food Store* via *the Galley to enable the Galley to be larger.”*
2. Mess and Galley are adjacent: *“Although in different compartments, connectivity is good.”*
3. Emergency Generator Room and Galley must be separated: *“Subordinate to other noise-related separation constraints.”*
4. Mess and Galley are separated: *“It's not possible to arrange both systems in the same compartment without introducing additional conflicts.”*
5. Mess and Medical Room should be separated: *“Solve noise issues with insulation?”*

4.3.3. Temporal aspects

Third, the development of concept designs over time is investigated. Fig. 12 shows the development of MoPs over time for all teams (except Team 1) for the two design problems. The following observations can be made:

1. The MoPs show convergence over time and limited rework of the layout, i.e., many local adjustments were made. In Section 4.1, it was observed that in later phases teams seemed to focus on finalising the layout, such that all systems fit. Major decisions were taken during the early phases. This could explain, for instance, why the SMoP has many plateaus: once systems are



(a)

(b)

Fig. 12. Development of MoPs over time.

positioned in preferred compartments, and teams keep to these decisions, SMoP will not change.

2. MoPs can indicate when alternative arrangements are made later in the design process. For instance, see the highlighted Team 7 for design problem 1 and Teams 3 and 7 for design problem 2 in Fig. 12. These teams moved systems across compartments relatively late in the design process, which can also be observed in the MoP traces. For example, Team 7 (design problem 1) compromises LMoP for a significant improvement in SMoP at 25 min of the experimental round.
3. The definition of MoPs can limit the amount of insight into the overall development of the concept design over time. For instance, both Logistics and Safety MoPs cannot consider interactions when systems are outside all compartments. Hence, the current LMoP and SMoP will not be able to provide absolute performance over the complete design process but can only be used to compare concept designs with the same systems arranged inside compartments. This problem could be partially addressed by adding a penalty to these MoPs when any system in an interaction is outside all compartments. However, useful MoP information may get obscured if penalty values are of the same order as the non-penalised version of the MoP.
4. In some cases, teams used a relatively long time to marginally increase the quality of the concept design. Both in post-experiment discussions and in the questionnaire, participants did indicate that the method could be more realistic if it could provide or be used to get insight into the costs and benefits (e.g., material, time, and effort) of design changes.

4.3.4. *Conclusion*

Concluding, from a design quality point of view, the second design problem more difficult. Specifically, this was due to the limited available area. Also, the results indicate that MoPs are valuable metrics to provide insight into the quality of the concept designs. However, a detailed manual evaluation of the concept designs is still required. Lastly, the results do not indicate that the design rationale method directly leads to qualitatively better concept designs compared to the baseline method. However, this could also be caused by the simple design problems used in this experiment. More complex design problems with multiple stakeholders will likely show more benefits.

4.4. *Satisfaction with generated concept designs*

The questionnaire was used to elucidate participant satisfaction with generated concept designs. For each round, participants were asked to respond to the following three statements:

1. *I'm satisfied with the layout from my role's perspective.*
2. *I'm satisfied with my input in the decision-making.*
3. *My input in the decision-making has been satisfactorily* incorporated in the final design.

Fig. 13 presents the satisfaction of participants with the three statements presented above. Generally, participants were satisfied with the outcome of the design process. There is little difference between the expressed satisfaction across the use of the two methods since the balance between Agree and Strongly Agree is almost equal for both methods.

Only one person expressed dissatisfaction with the three statements when using the baseline method. This participant (the Logistics Specialist in Team 8) was unsatisfied with the outcome of design problem 2. From an MoP perspective, this is notable since Team 8 achieved a good performance from a logistics perspective (third best of all teams). This Logistics Specialist proposed to switch the positions of Food Store 1 and the EGR in the layout shown in Fig. 11(e). The Naval Architect (who operated the tool) objected without argumentation to implement this proposed change. Implementing this change would have resulted in an improvement of the LMoP by 3.9 for a reduction of 3.2 of the AMoP. However, this trade-off between Logistics and Area was not further discussed by the team. Hence, the question is whether the Logistics Specialist was dissatisfied with the layout, the team process, or both. Also, it would be interesting to know whether the satisfaction would be different if the actual MoP values were known to the team.

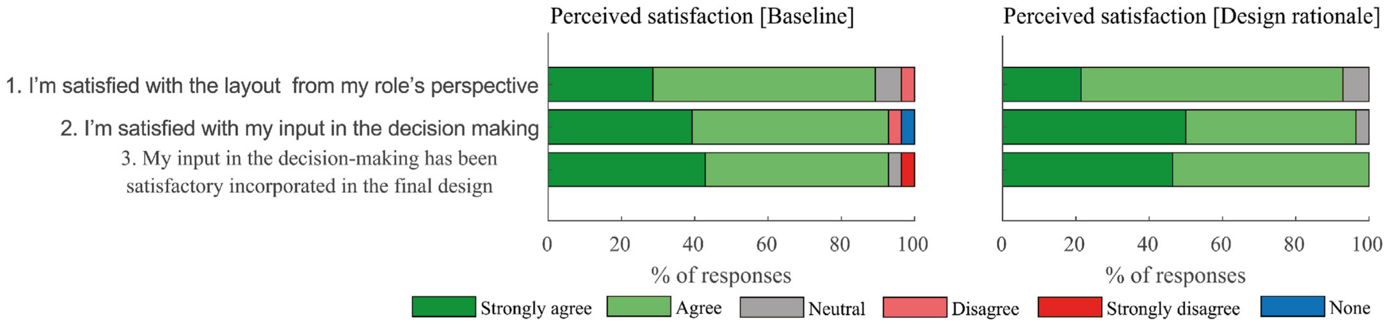


Fig. 13. Satisfaction with quality of concept designs - comparison between baseline and design rationale method (n = 28).

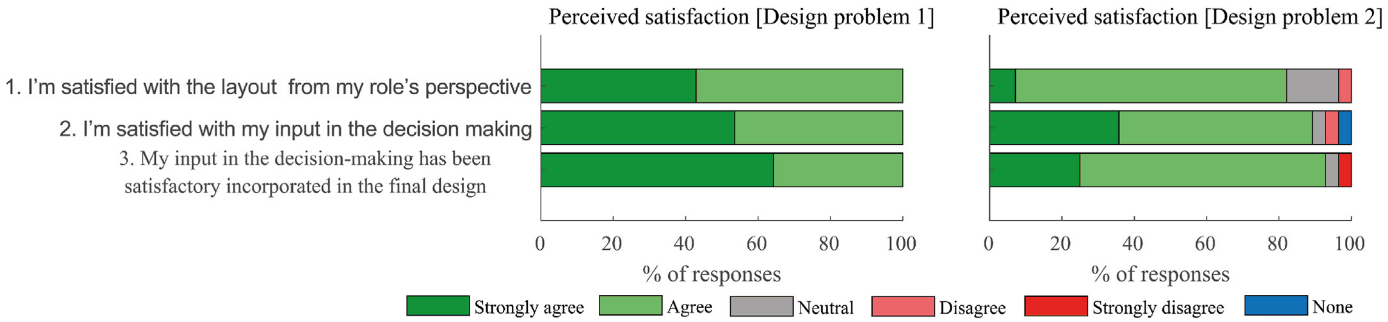


Fig. 14. Satisfaction with quality of concept designs - comparison between two design problems (n = 28).

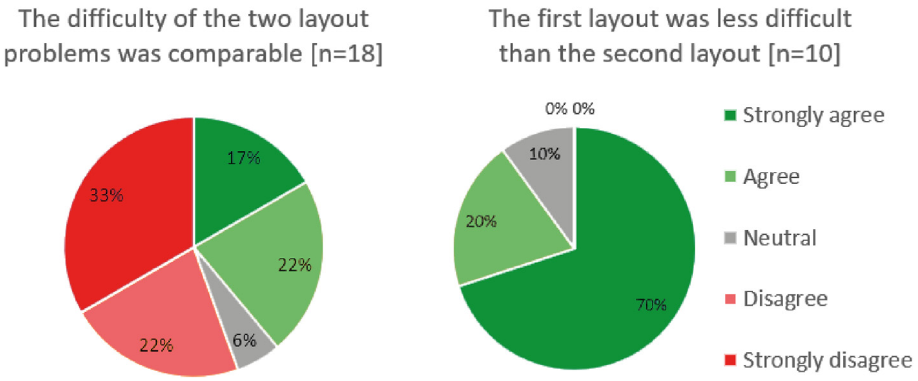


Fig. 15. Perceived relative difficulty of design problems.

Interestingly, this Logistics Specialist, when asked to describe how the design rationale method supported decision-making, replied:

> "[It forces] a holistic approach to the design problem, instead of [allowing] for alpha behaviour to push your own interest."

So, this participant perceived the design rationale method to indeed support the collaborative design decision-making process.

Fig. 14 presents the same satisfaction of participants, yet differentiated between the two design problems. For the first design problem, all participants expressed to be satisfied with the concept designs. 64% strongly agreed that the input was satisfactorily incorporated in the concept design. For the second design problem, most participants are satisfied with the outcome of the design process. Compared to the first design problem, fewer participants strongly agreed with the statements. A possible explanation is the difficulty of the design problem. As shown in Fig. 15, most participants experienced dissimilar difficulties across the two design problems (left), of which the second design problem seemed to be more challenging (right).[4] Indeed, in the second design problem, significant compromises were needed regarding system sizing, while the first design problem mainly contained concessions regarding relative positions (i.e., logistics and safety). This was already shown in Section 4.3.

Concluding, the analysis in this section indicates that participant satisfaction with the generated concept designs was generally good and is dependent on the difficulty of the design problem. Also, the single case where a participant was not satisfied with the outcome supports the conclusion of Section 4.2.

4.5. Perceived benefits

In this section, the participants' perception of the design

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[4] This question was changed during the execution of the experiments, hence the split in *n*.

rationale method is investigated. This investigation is done based on the following open questions from the questionnaire:

1. *Which functionalities of the design rationale method were most useful to the design case?*
2. *What additional functionalities of the design rationale method would be beneficial?*
3. *Would the design rationale method be beneficial for design (review) sessions, and why?*

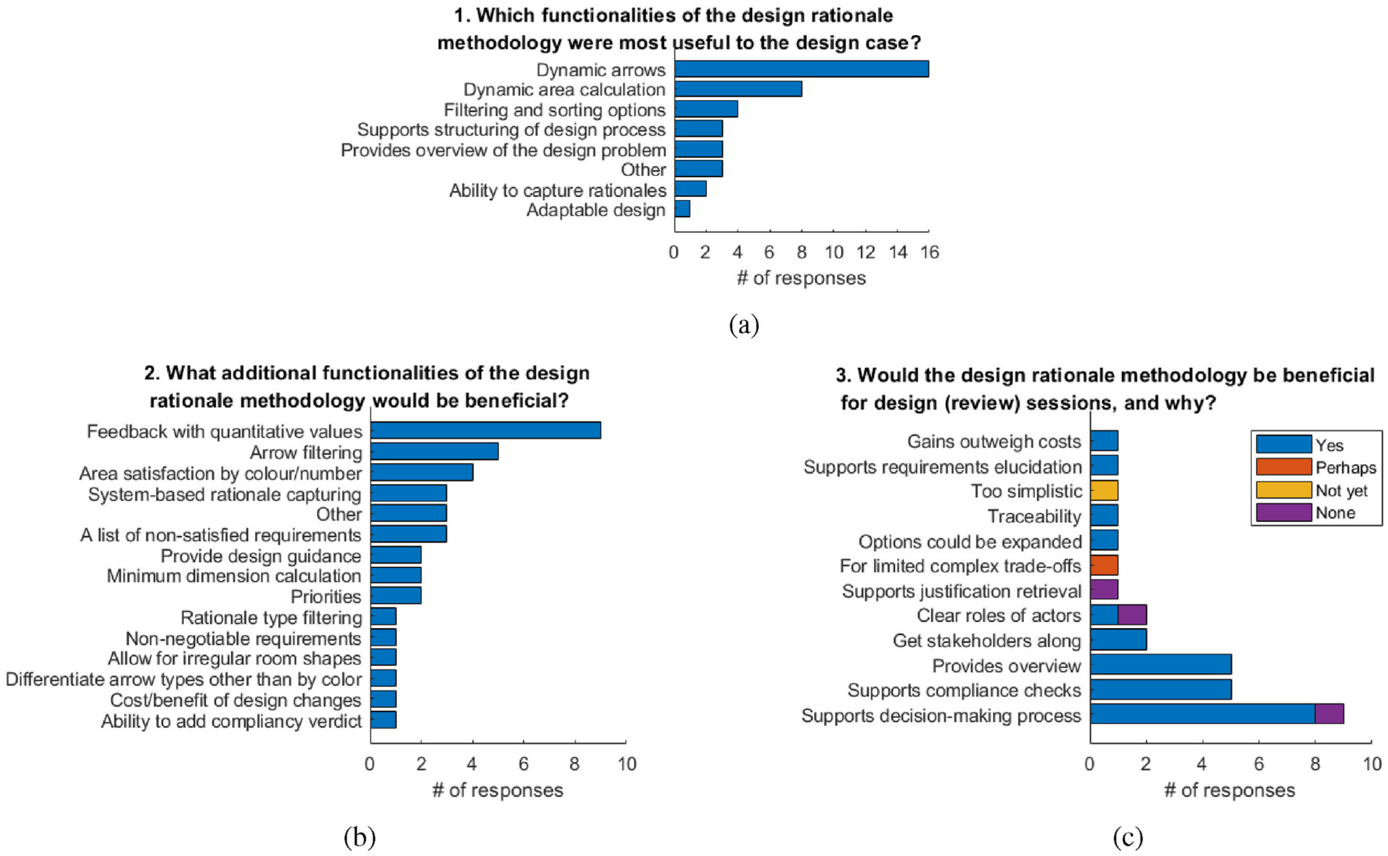
The responses to these three questions are coded by the primary author and are visualised in Fig. 16(a) to (c), respectively.

First, participants were asked which functionalities of the design rationale method were most useful during the experiment. Based on Fig. 16(a), the dynamic annotations (arrows and area calculation) were mentioned 16 and 8 times in responses to this question. Four participants found the filtering and sorting of design rationale useful. Capturing design rationale itself was mentioned only 2 times. A possible explanation is that the action of design rationale capture takes much effort and only becomes useful when the captured design rationale is used, for instance, via design rationale retrieval and dynamic annotations to create an overview of the design problem (n = 3).

Second, the questionnaire was used to elucidate any additional functionalities thought to be beneficial to the design rationale method, Fig. 16(b). Participants would like to receive quantitative feedback (n = 9), visual and textual feedback on area satisfaction (n = 4), and a list of non-satisfied requirements (n = 3). Furthermore, five participants indicated that filtering the arrows would be beneficial. In a post-experiment discussion with one of the teams, participants explained that they would rather have annotations on demand (i.e., to show relevant parts of the interactions network), instead of the visualisation of the entire network as currently implemented. For the relatively small design cases in the experiment, the network was already quite extensive, see Fig. 2. Three participants indicated that the ability to capture design rationale related to single systems is missing. For instance, Team 5 decided to exclude the Emergency Generator Room to solve the mismatch between available and required areas (Section 4.3) and commented that they were not able to capture this decision and justification by the design rationale method.

Third, while Question 1 asked for the benefits of the design rationale method to the *design case in the experiment*, Question 3 required participants to consider the use of the design rationale method in *actual design (review) sessions*. Participants were asked: “Would the design rationale method be beneficial for design (review) sessions, and why?” Fig. 16(c) shows that most participants answered ‘yes’ but two participants considered this ‘not yet’ or ‘perhaps’ the case. Three participants only provided an open response (i.e., ‘none’). The doubting participants participated in the same team and considered the design rationale method ‘too simplistic’ or ‘maybe applicable for design problems with limited complexity’. This leads to the question of whether group experience is related to design tool acceptance. Most participants considered the design rationale method beneficial to design (review) sessions because it would support the decision-making process (n = 9), support compliance checks (n = 5), and provide an overview (n = 5).

Concluding, participants were generally positive about the benefits of the design rationale method, both for the design case and actual design (review) sessions. Further, the participants expressed potential additional functionalities.



(a)

(b)

(c)

Fig. 16. Perceived benefits and required additional functionalities of the design rationale method.

5. Discussion

Although the experiment results show the benefits of the developed design rationale method, currently, the method is tailored to the design experiment. Therefore, the range of implemented design rationale types was limited. To make the design rationale method more suitable for actual ship design problems, attention must given to the representation and capturing of realistic ship layout design decisions, for instance, by expanding the interaction definition and inclusion of system properties and compromises (DeNucci, 2012; le Poole et al., 2022b).

The conducted experiment has some limitations as well, namely:

1. Although the design rationale method is implemented in Rhinoceros, an integration with ship design tools is currently missing. Therefore, the interplay between real ship design tools and the design rationale method could not be investigated. Therefore, the research assumes that the 'manual' design work is similar to using a human-centric ship layout design tool, such as Andrews and Dicks (1997); Takken (2009). Although such design tools provide more functionality, the observed use of the design rationale method indicates that participants used it partly to 'sketch' during the negotiation process. Applying more computer-centric ship layout design tools, such as Van Oers (2011), will likely need a different implementation and process than presented here and is probably more focused on exploration and post-processing (Duchateau, 2016; DeNucci, 2012). Also, the long-term (i.e., multi-session) effects of applying the design rationale method have not been evaluated. However, some of the beneficial functionalities of the design rationale method mentioned by participants also apply to the multi-session use of the method. For instance, it provides an overview, traceability, and justification retrieval, and it helps to involve stakeholders.
2. Design considerations were typically verbally discussed by design teams, but not always supported by, for instance, 'network arrangement'. To get insight into such discussions leading up to the capture of a rationale, audio or video recordings of design sessions could be a useful data source to get further insight into the role of design rationale in collaborative design decision-making.
3. Both groups of participants (experts and students) have their limitations concerning the experiment. On the one hand, experts are likely biased by their own experience with actual ship design processes and are likely to have reflected their thoughts in their responses (Andrews, 2022a). For instance, the participants doubting the usefulness of the design rationale method for actual design implicitly relate their response to their view of ship design. For example, one participant said design rationale method is 'too simplistic'. Since ship design is much more complex in reality, this participant doubted if the method would stand in such a more complex environment. On the other hand, students are likely to lack ship design experience. Some of them will have studied ship design before, but some of the students might have joined the Maritime Engineering master program from a non-ship design background. Also, the demographic and corresponding cultural diversity between students is likely higher than in the expert group. This might contribute to significantly different group dynamics - and perhaps different outcomes of the design process. Due to the absence of audio recordings, this aspect could not be further investigated. The combination of students and experts is thought to give balance to bias to own experience and the perception of the design rationale method.
4. Unfortunately, the number of participants in the experiment was limited. It proved especially hard to recruit students. As a result, statistically significant results could not be obtained. Nevertheless, the quantitative and qualitative results obtained in the experiment give valuable indications for further development of the design rationale method.

Based on the presented work, the following topics are deemed relevant for future research:

1. Further developments of the design rationale method, which include: a larger variation of design rationale types, including System Properties; filtering of annotations; and filtering based on keywords. Furthermore, the applicability of the design rationale method in multi-session design for larger design problems (e.g., full ship size), the reuse of design rationale between iterations at various levels of design (e.g., macro, major, micro), and the integration with actual ship design tools have to be investigated. Attention must paid to the role of layouts in the overall ship synthesis process. For instance, how can the method help to capture rationale related to resistance, style, or identified design drivers?
2. The development of a process description to guide designers in exploiting the opportunities of the design rationale method. For instance, Team 9 captured additional design rationale after finishing the design to explain design choices, i.e., performed reflection on the final design (and design process). Prescribing such steps would guide all users in how to best use the design rationale method.
3. An evaluation of the usefulness of MoPs during actual design work. How do designers use these MoPs in practice, and how to avoid the excessive focus on optimising MoPs, as emerged during the practice run of the experiment? Also, which design rationale-based MoPs are suitable for real ship design, and how to ensure these consider the right set of design rationale?

These future developments are expected to enhance the method. Yet, the method should be used judiciously as the naval architect is, ultimately, responsible for design choices. As such, any insight and information provided by the design rationale method, as with any other source of information, should be carefully considered.

6. Conclusions

The availability of design rationale, i.e., the justifications behind design decisions, in complex ship design is key as a knowledge base for the multiple participating actors and to performing informed iterative design. Currently, there is no suitable design rationale method that considers the multi-actor decision-making aspect of complex ship design. Therefore the goal of this paper was twofold, namely:

1. To develop a design rationale method to aid designers in the continuous capturing and reuse of design rationale during the collaborative concept design process, and
2. To evaluate how the developed design rationale method benefits collaborative design decision-making such that it leads to better insight into design issues across the design team and better concept designs during a single design session.

The development of a proof-of-concept design rationale method and its integration in design tool Rhinoceros, as described in Section 2, meets the first goal. This design rationale method allows designers to capture design rationale while designing. This provides both short-term benefits (e.g., to create a common knowledge base during design sessions) and long-term advantages (e.g., review of the context of past design decisions before changing a concept design).

The results of the design experiment with students and experts in the field of complex ship design, described in Sections 3 and 4 indicate that using a design rationale method while designing a layout can have both measurable and perceived benefits. An example of the former is that the design rationale method motivates teams to use ‘network arrangement’, as indicated by the results (Section 4.1). Such network arrangement of systems visually supports the team in sketching the initial arrangement of systems. Participants generally perceived the design rationale method to facilitate enrichment and negotiated knowledge (Section 4.2), aspects aiding to provide a better understanding of the design problem within the entire design team.

Although further development and long-term testing need to be performed, the results of this paper indicate that the proposed and evaluated design rationale method is a valuable addition to support collaborative design decision-making for complex vessels.

Disclaimer

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 Materiel and IT Command, or the Royal Netherlands Navy.

Supplementary

The data underlying the case study, as well as detailed tests of the method presented in the paper can be found in the following repository: https://doi.org/10.4121/21502338. 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 Materiel and IT Command of the Netherlands Ministry of Defence.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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