INTERACTIVE MULTI-CONSTRAINED SYSTEM-TO-COMPARTMENT ALLOCATION TO SUPPORT REAL-TIME COLLABORATIVE COMPLEX SHIP LAYOUT DESIGN DECISION-MAKING

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Synopsis

The development of concept designs during early warship design stages is essential to inform stakeholder dialogues on technical feasibility, affordability, and risk. One of the key aspects of warship concept designs is the layout of systems in the overall arrangement. The adoption of real-time design processes, such as concurrent design, require naval architects to use layout design tools in a more dynamic setting than during traditional design review session-based design processes. This paper investigates how ship layout design tools can be used in a real-time manner. It does so by considering the arrangement problem of allocating systems to compartments, subject to available and required area, global system position preferences, and preferred relative system positions.

An existing ship layout design tool, WARGEAR, is extended to consider global and relative system constraints, and is integrated in a proposed method for the allocation of systems to compartments. Furthermore, a novel two-item correlation metric is developed to support designers in the analysis of the, typically large, design space. The metric can be used to identify conflicts and trade-offs between design parameters, as well as promising combinations of design parameters.

Two case studies (8 and 89 systems respectively) are used to demonstrate and evaluate the proposed method. Based on these case studies, the calculation time or accuracy of the allocation method does not seem to be the main issue for collaborative design decision-making. Indeed, most effort is required for the analysis of the generated concept designs. Since this is not a problem as such, the real-time use of automated design tools to evaluate the impact of proposed design changes seems to be a promising way to enhance the effectiveness of collaborative ship layout design sessions.

Keywords: Early stage design; layout design; system allocation; concurrent design; stakeholder dialogue; WARGEAR

1 Introduction

Compared to most of their merchant counterparts, naval vessels have multiple functions to fulfil a wide variety of operational tasks across the full spectrum of violence. Since the relative importance of these functions is hard to express, "the early stages of warship design inevitably and quite properly become a colloquy involving naval staff, constructors, naval architects, weapon designers and other specialists" (Brown, 1986). Hence, early stage design of naval vessels has been described as a wicked problem (Andrews, 2011, 2018) - a type of problem where there is no consensus on either the problem or solution (Roberts, 2000). Therefore, defining the engineering problem (i.e. setting the requirements) can be as, or even more, challenging than generating solutions (i.e. concept designs). Andrews (2011) advocates a process of requirements elucidation to solve this challenge. Requirements elucidation involves a dialogue between all relevant stakeholders, supported by insights into technical and financial feasibility and risk (Van Oers et al., 2018; Andrews, 2011). Because the early stage design problem can be very fluent, stakeholders need to settle on negotiated knowledge, i.e. an established negotiated basis of correctness of information to allow for interaction between actors with different perspectives on that information (le Poole et al., 2022a; De Bruijn and Ten Heuvelhof, 2008, p70). To find the insights required to support such dialogue, concept designs need to be generated (Andrews, 2011; Van Oers et al., 2018; Duchateau, 2016). Such concept designs need

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Authors' Biographies

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Prof. Ir. Hans Hopman is professor Ship Design and was head of the Department of Maritime and Transport Technology at Delft University of Technology. His research focuses on the improvement of the design process for complex ships and marine systems integration. He started his academic career in Delft in 2006 after having worked nearly 25 years for the Directorate Materiel Royal Netherlands Navy where he was involved in many naval procurement programmes.

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to include, for instance, marine propulsion system and distributed system design as well as the overall layout of the vessel (i.e. general or functional arrangements). The latter is especially important because the layout is the integrated description of all individual systems, and is input to many other ship design tasks. Also, naval ships are often space critical, i.e. their size and costs are governed by spatial requirements (Carlson and Fireman, 1987; DeNucci, 2012).

One development to support alignment of stakeholders during early stage design, and upcoming for warships, is 'concurrent design' (Bandecchi et al., 2000). Contrary to traditional design review sessions, in concurrent design, all relevant stakeholders (e.g. clients and engineers) are involved in (high level) design work in a co-located setting, to settle on meet a predefined goal. Such goals could be, for instance, to solve a particular design problem, to settle on main design parameters, or to define a concept of operations. Arising design issues are addressed immediately in a holistic manner, i.e. all stakeholders can provide input from their point of view. Hence, design decisions are more likely to be taken under consensus. Detailed design work is typically done by the engineers between concurrent design sessions. Benefits of concurrent design include: 1) generation of higher quality results within a shorter time-frame and 2) more effective, interactive and transparent response and contribution to the evolution of the complete system design by engineers, rather than to individual design elements in isolation (Bandecchi et al., 2000). Commencing in space craft and mission design at the European Space Agency (ESA) (Bandecchi et al., 2000), concurrent design has recently been applied in ship design in the Netherlands as well (NIDV, 2022; Feadship, 2017).

Traditionally, ship design is structured around design work, design review, and subsequent design work (Duchateau, 2016). Therefore, current ship design tools, tailored to such design review-based processes, are not always suitable for real-time design. For example, Packing (Van Oers, 2011) requires multiple hours to automatically generate a set of concept designs. More human-centric design tools, such as Design Building Block approach (Andrews and Dicks, 1997) and FIDES (Takken, 2009), might be too labour-intensive. As a consequence, designers mainly rely on experience and judgment, as well as reasoning, to assess potential risks of proposed design changes. In situ, design changes are evaluated in a speculative manner, i.e. thinking through 'what-if' scenarios. Subsequent design work (after sessions) might reveal unforeseen sizing and integration challenges.

With the adoption of concurrent design, the speed of the design process increases, compared to traditional design processes (Bandecchi et al., 2000). For concurrent design sessions aimed at design work, current ship layout design tools might be unable to keep up with the highly iterative nature of concurrent design. Hence, if the speed of the design process changes, layout design tools need to be adapted or developed accordingly, for two reasons:

1. Time and resources are often limited during early stage design. To allow for timely feedback on feasibility, affordability, and risk, new and updated concept designs need to be generated quickly (Duchateau, 2016).

2. Design tools need to be responsive and non-rigid to allow designers to address emerging design problems (Andrews, 2011). Slow tools might encourage designers to use quicker, but potentially less accurate, design tools. Such tools might be developed for a different scope, which introduces additional risk and assumptions. Hence, unresponsive and rigid tools can damage the design process (Duchateau, 2016).

Although it is not likely that all design work can be performed during concurrent design sessions, it is expected that the effectiveness of design sessions could be improved if the impact of proposed layout design changes could be evaluated in real-time using suitable interactive (i.e. automated) design tools. This way, stakeholders could be informed on feasibility and risk while dialogues proceed, and thus the up-to-date design insight adds to expert judgement. Hence, the question this paper aims to answer is: how can automated design tools for ship layout design be used in a real-time manner? That is: 1) how can such tools be used to generate concept designs in real-time, and 2) how can these concept designs be analysed in real-time?

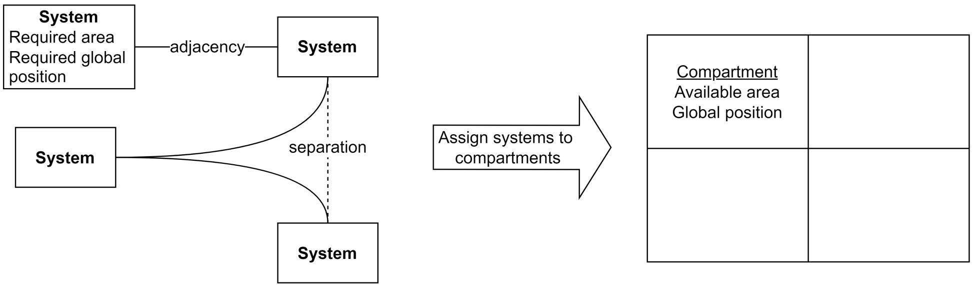


Figure 1: Visual explanation of the systems-to-compartments allocation problem

To answer these questions, this paper investigates the allocation of systems to compartments, as illustrated in Figure 1. This design problem is highly dimensional (due to the high number of design options (Duchateau, 2016)), is subject to many spatial constraints (e.g. compartment sizing), and has impact on the ship's performance (e.g. logistics, stability, and vulnerability of distributed systems), and is input to many design disciplines. Additionally, design parameters can be highly interdependent (e.g. available area in compartments versus required area and global position for systems as well as relative positions between systems). Finally, the allocation of systems to compartments can be a starting point for more detailed layout design (e.g. Medjdoub and Yannou (2000); Nick (2008); le Poole et al. (2022c)). Hence, this problem is considered to be a suitable example of overall ship layout design.

Various research investigated the system-to-compartments allocation problem. For instance, see Nick (2008); Gillespie (2012); Stevens (2016); le Poole et al. (2022c). In this paper, the allocation algorithm implemented in the WARGEAR (WARship GEneral ARrangement) methodology (le Poole et al., 2022c) is extended. Section 2 describes this extended method, and how it can be used to generate design insights to support real-time collaborative design decision-making. Subsequently, Sections 3 and 4 describe the demonstration and testing of the allocation method in a small and large case study. Finally, Section 5 concludes the paper, and evaluates how automated design tools might be applied during collaborative design of ship layouts, as well as identifies potential issues that might need to be resolved.

2 Method

2.1 Overview

An overview of the allocation method is presented in Figure 2. At the top level, the method consists of three steps, namely:

1. *Input*. This step is human-centric.
2. *Allocation*. In this step an automated allocation tool is used to generate concept designs.
3. *Analysis*. This step is human-centric again.

The human-centric steps are expected to be most time consuming, but cannot be eliminated because it's also in these steps (especially during Analysis) that most learning occurs. The three steps are further elaborated below.

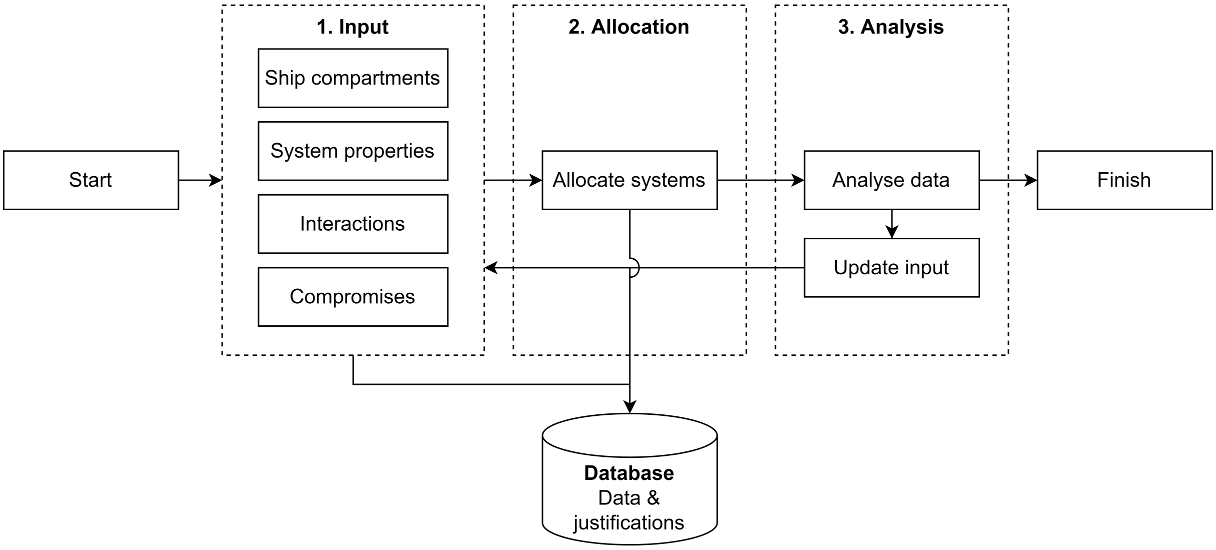


Figure 2: High level overview of the proposed method

When used in an actual design process, the availability of a dedicated database for storage of data related to the three steps Input, Allocation, and Analysis is considered to be important. Indeed, Duchateau (2016) notes that, on one hand, if "the user has to wait for long periods between each iteration [...] he or she will likely lose focus or fail to keep track of the decision steps in each consecutive iteration." On the other hand, Duchateau mentions that problems (e.g., fatigue and loss of focus) may be caused when human-computer "interaction moments follow in quick succession, especially when dealing with a large amount of complex results." In real-time collaborative decision-making processes, both types of interaction frequencies will appear - between and within design sessions respectively. Hence the storage of design data (and supporting rationale) for later retrieval is expected to benefit the designer and the overall design process. See also DeNucci (2012) and le Poole et al. (2022b).

2.2 *Input*

The input to the method comprises:

- *Ship compartments*: Transverse bulkheads in naval ship are often driven by damage length considerations and required space for larger systems such as engine rooms, or main sensors masts which require sufficient structural support. The compartmentisation of the concept design is generated via bulkhead and deck positions, as well as deck area per compartment. This could be extended to include, for instance, available volume per compartment. Each compartment is assigned a vertical and longitudinal global position, describing where the compartment is situated in the ship.

- *System Properties*: this is a list with systems and their respective properties. These properties are, for example, required area and volume, or preferred global positions. Currently, the method considers required area and global positions of systems. The latter are expressed in terms of the global positions of compartments.

- *Interactions*: are preferred or required spatial relationships between systems or System Properties (DeNucci, 2012; le Poole et al., 2022b). Originally, WARGEAR required designers to link systems to particular functional building blocks or compartments (le Poole et al., 2022c). Based on these relationships, WARGEAR would assign systems to compartments. However, it was not able to group or spread systems based on interactions between systems. Currently, the following five interaction types have been implemented:

ID	Description	Explanation
1	Compartment adjacency	systems need to be in the same compartment.
-1	Compartment separation	systems need to be in different compartments.
2	Maximum Manhattan distance	systems can be separated by a maximum Manhattan distance. the Manhattan distance is calculated between compartment centroids, since a precise position for each space is not available yet.
-2	Minimum Manhattan distance	systems should be separated by a minimum Manhattan distance.
-3	Minimum radial separation	systems should be separated by a minimum number of compartments.

These interaction types are visualised in Figure 3.

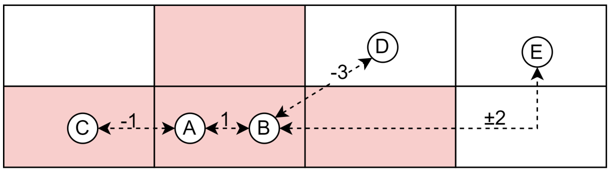


Figure 3: Visual representation of implemented interaction types. A–B: Compartment adjacency; A–C: Compartment separation; B-D: minimum radial separation; B–E: minimum/maximum Manhattan distance.

- *Compromises*: the preferred solutions to a set of conflicting or competing interactions (DeNucci, 2012) or System Properties (le Poole et al., 2022b). Currently, compromises are not implemented in the tool, but is considered to be a useful feature. Indeed, this would allow the tool to make trade-offs in line with what the human designer prefers.

System Properties, Interactions, and Compromises also comprise a justification. For instance, an interaction is *the ammunition store should be adjacent to the gun* [relation], *to reduce dangerous transport of ammunition through the ship* [justification] (le Poole et al., 2022b). In this paper, the justification for the input is not explicitly used by the tools, but might be useful for retrieval during actual decision-making, as mentioned in Section 2.1.

2.3 *Allocation*

As mentioned before, the method used to allocate systems to compartments is an extension of the method implemented in WARGEAR (le Poole et al., 2022c). For sake of brevity, this paper will provide a high level overview of the allocation method and elaborate on its extensions. A flowchart of the adapted allocation method is provided in Figure 4. Elements with grey shading have been added or adapted from the original version. In short, the extensions and adoptions comprise:

1. The inclusion of global position and interaction constraints.

2. Relaxation of these constraints in cases where these are too restrictive.

3. The option to use multiple system sorting algorithms, to enable different allocation sequences.
4. The option to perform the allocation multiple times, to achieve a more precisely defined design space.

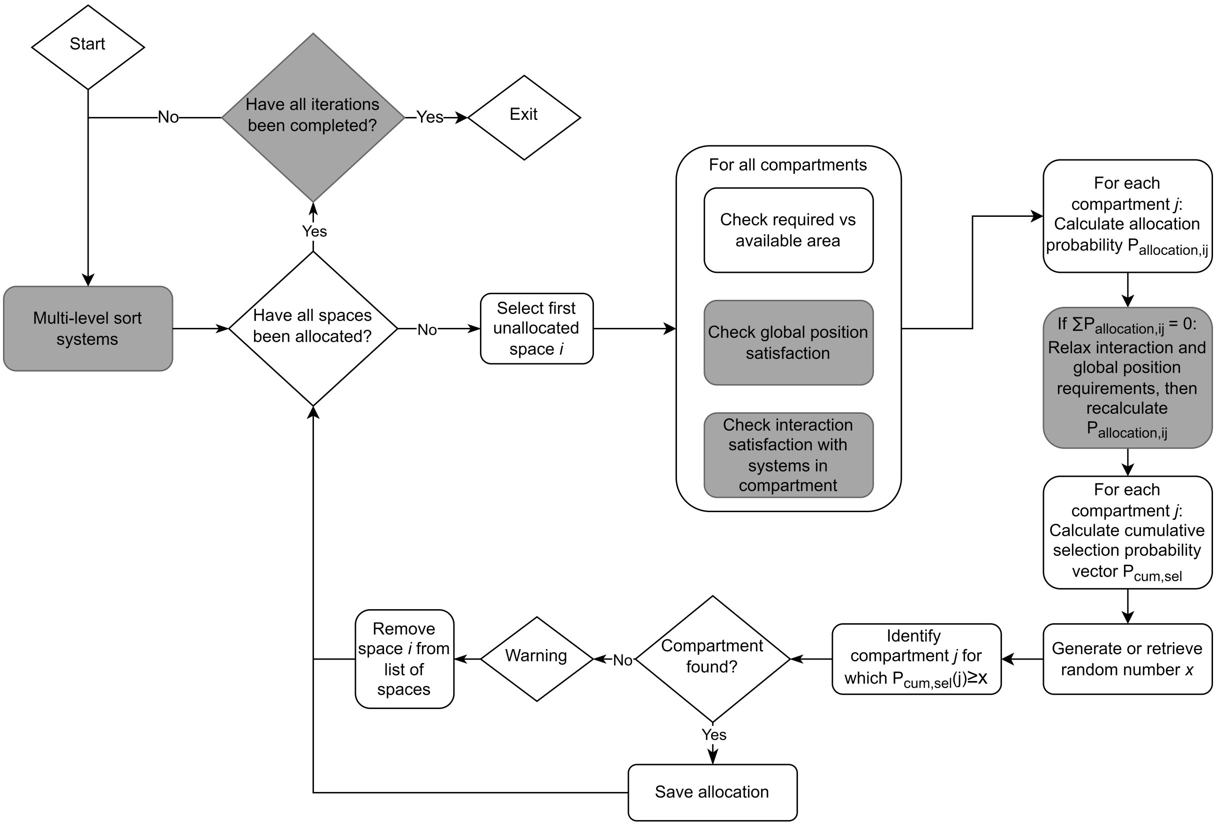


Figure 4: Flowchart of the allocation calculations, based on (le Poole et al., 2022c). Grey shaded elements represent extensions and adaptions for this paper.

To determine which compartments are available for allocation of system i, the following three aspects are considered.

First, the available area in a compartment needs to be sufficient to accommodate system i. The available area $A_{available,j}$ in compartment j is defined by Equation 1. This Equation takes into consideration that the available area decreases when systems get allocated to compartment j.

$$A_{available,j} = A_{compartment,j} - A_{allocated\,systems,j} \tag{1}$$

Second, a compartment needs to fulfil specified System Properties, such as global positions. If a system needs to be high up in the ship, compartments that are located high up are more preferred than compartments situated at the bottom of the vessel.

Third, suppose a designer has defined interactions between a set of systems. For the sake of this explanation, assume these are adjacency relationships. If one or more of the systems related to this defined interaction is already allocated, the other systems need to be allocated to the same compartments, or neighbouring compartments in case the same compartments are not available.

le Poole et al. (2022c) defined the probability $P_{allocation,ij}$ that system i is allocated to compartment j as a way to differentiate between available and preferred compartments. This probability takes into account the considerations for preferring or ignoring compartments. $P_{allocation,ij}$ is given by Equation 2, and has been adapted from the original formulation to include global positions and interactions. The cumulative selection probability $P_{sel,ij}$ that compartment j is selected for system i is given by Equation 3. Subsequently the cumulative selection probability vector for the allocation of system i ($P_{cum,sel}$) is given by Equation 4. For a more detailed explanation of these equations, refer to le Poole et al. (2022c).

$$P_{allocation,ij} = \begin{cases} \frac{A_{available,j} \cdot N_{intsat,j}}{Degree_{comp,j}} & \text{if } A_{available,j} \geq RA_i \text{ and } GP_j = GP_i \text{ (if } GP_i \text{is specified)} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

Where:

$N_{intsat,j}$ is the number of interactions between already allocated systems and system i, that will be satisfied if system i is allocated to compartment j. If there are no such interactions, $N_{intsat,j} = 1$.

GP_i and GP_j are the global position of system i and compartment j respectively.

$Degree_{comp,j}$ is the number of systems a compartment is connected to, based on GP.

$$P_{sel,ij} = \frac{P_{allocation,ij}}{\sum_{j=1}^{N_{comp}} P_{allocation,ij}} \qquad (j = 1,2,...,N_{comp}) \tag{3}$$

Where:

N_{comp} is the number of compartments.

$$P_{cum,sel}(j) = \sum_{n=1}^{j} P_{sel,ij} \qquad (j = 1,2,...,N_{comp}) \tag{4}$$

If $P_{allocation,ij} = 0$ for all compartments, no compartment is available that satisfies required area, global position, and interaction requirements. In such cases, the global position and interaction requirements are relaxed, and $P_{allocation,ij}$ is recalculated. Figure 5 shows that adjacent compartments to compartments that would satisfy global positions or interactions become preferred compartments after relaxation. Note that other relaxation rules are possible, e.g. to only extend to compartments at the same deck.

Figure 5: Compartment preference before (black) and after relaxation (grey)

As in le Poole et al. (2022c), a roulette wheel selection method is used to select between available compartments for system i. In general, roulette wheel selection assumes that the probability of selection is proportional to the fitness of an individual. If N individuals are considered, each with a fitness $w_i > 0 (i = 1,2,...,N)$, then the selection probability of individual i is given by Equation 5 (Lipowski and Lipowska, 2012).

$$p_i = \frac{w_i}{\sum_{i=1}^{N} w_i} \qquad (i = 1,2,...,N) \tag{5}$$

Subsequently the roulette wheel is constructed with sectors whose size is proportional to $w_i\,(i = 1,2,...,N)$. Selection of an individual is done by randomly selecting a point x at the roulette wheel and identifying the corresponding sector (Lipowski and Lipowska, 2012). In WARGEAR, $p_i = P_{cum,sel}$ (le Poole et al., 2022c).

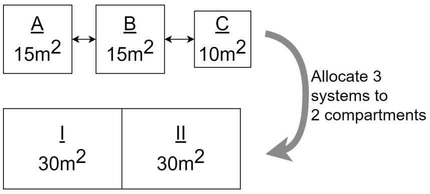


Figure 6: Setup of three systems to be allocated to two compartments.

To illustrate this procedure, consider three systems A ($15m^2$), B($15m^2$), and C($10m^2$) need to be allocated to two compartments I($30m^2$) and II($30m^2$), shown in Figure 6. Two interactions are defined between systems A-B and B-C, meaning systems in these pairs need to be adjacent, i.e. in the same compartment. The available area in none of the compartments is sufficient to accommodate all three systems. Table 1 summarises the calculation of $P_{allocation}$ for the two compartments. The systems are allocated in the order A, B, C. For system A, any compartment can be chosen with equal probability. Assume compartment I is selected for system A. Consequently, system B will be allocated to compartment I as well to satisfy interaction A-B. Finally, the allocation of system C fails because of the need to satisfy interaction B-C and insufficient available area in compartment I. Relaxation of the

Table 1: Allocation of systems A, B, and C to compartments I and II. 1): Underlined text indicates selected compartments. 2): $P_{allocation} = 0$ for both compartments, hence the interaction requirement is relaxed. 3): due to relaxation, compartment II becomes available for system C.

	Allocate system A		Allocate system B		Allocate system C		Allocate system C (after relaxing interaction B-C)	
	Compartment		Compartment		Compartment		Compartment	
	I	II	I	II	I	II	I	II
$A_{available}$	30	30	15	30	0	30	0	30
$Degree_{comp}$	1	1	1	1	1	1	1	1
$N_{intsat,j}$	1	1	1	0	1	0	1	$1^{3)}$
$A_{available} \geq RA$	1	1	1	1	0	1	0	1
$GP_j = GP_i$	1	1	1	1	1	1	1	1
$P_{allocation}$	$\underline{30}^{1)}$	30	$\underline{15}$	$0^{2)}$	$0^{2)}$	0	0	$\underline{30}$

interaction requirement allows system C to be allocated to compartments adjacent to preferred compartments, i.e. compartment II.

The output of the allocation phase is a set of allocations, i.e. preliminary layouts of compartments with allocated systems, and data describing the performance of these layouts with respect to the input. For instance, the data describes which system properties and interactions have been satisfied.

2.4 Analysis

The analysis of the data generated by the allocation method can lead to insights, which can be used in subsequent design decision-making. The analysis process is very much human-centric, and involves exploring and working with the data (i.e. data *exploration*) (Duchateau, 2016). To guide the analysis process, the following aspects need to be investigated (Duchateau, 2016):

1. Identify how, when, and why design parameters relate. This includes the identification of positive (i.e. re-enforcing) interdependencies as well as conflicting relationships.
2. Identify how these conflicts might be resolved or avoided.

To support the exploration to answer these questions, designers might make use of (dynamic) visualisation and filtering of the data (Van Oers, 2011; Duchateau, 2016; Gaspar et al., 2014). This paper proposes the following three-step analysis process:

1. *Identify nature of design parameter relationships.* That is, the naval architect is to identify whether design parameters are likely to conflict and to what extent. One means to quantify such relationship between design parameters is correlation. In terms of the general arrangement of ships, high correlation between two design parameters means that these parameters can both likely be satisfied. For example suppose two systems with each a parameter 'area'. A high positive correlation between these two area parameters indicates that, across the set of concept designs, the two systems often satisfy these design constraints. Therefore, correlation can be a powerful means to get insight into the relationships between all pairs of design parameters, although this will require appropriate visualisation. To quantify these relationships, the ϕ coefficient of correlation (Garrett, 1958, p389) can be used to calculate the correlation between the binary satisfaction of all pairs of design parameters across the (potentially filtered) set of generated concept designs. The ϕ coefficient is given by Equation 6 (Garrett, 1958), in which $A-D$ refer to the four quadrants in Table 2.

$$\phi = \frac{AD - BC}{\sqrt{(A+B)(C+D)(B+D)(A+C)}} \tag{6}$$

Table 2: Matrix for calculation of coefficients of correlation between two binary items. A-D: number of observations in data set. $\phi = -0.58$, $r_t = -0.05$ and $r_c = 0.43$ for the example (right)

		Item 1	
		No	**Yes**
Item 2	**Yes**	B	A
	No	D	C

		Item 1	
		No	**Yes**
Item 2	**Yes**	6	10
	No	1	4

Although the ϕ coefficient of correlation provides a measure of correlation between two binary items, it does provide only limited insight into the *extent* that both items can be satisfied. For example, ϕ does not communicate the balance between A and D. Hence, ϕ cannot be used to inform the designer whether two items can generally be satisfied (i.e. A is larger than D) or if they can generally not be met simultaneously (i.e. A is smaller than D). Therefore, a new two-item correlation metric has been developed to quantify to which extent two items can be satisfied relative to the extent in which both or one of the items needs to be compromised.

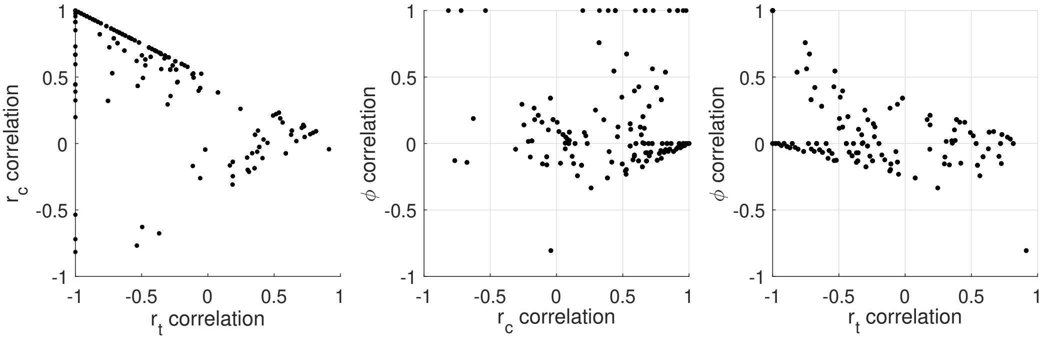
The first metric, r_t, is provided by Equation 7 and describes in how many cases two items need to be traded off against each other, i.e. one can choose only item 1 or only item 2. If $r_t = -1$, there are no cases in which there is a strict trade-off necessary. If $r_t = 1$, there is a conflict between the two items in all generated concept designs. If $r_t < 0$, less than half of the cases comprise a conflict. The remaining cases comprise either cases where both items are satisfied and cases where neither of the cases is satisfied.

$$r_t = 2\frac{B+C}{A+B+C+D} - 1 \tag{7}$$

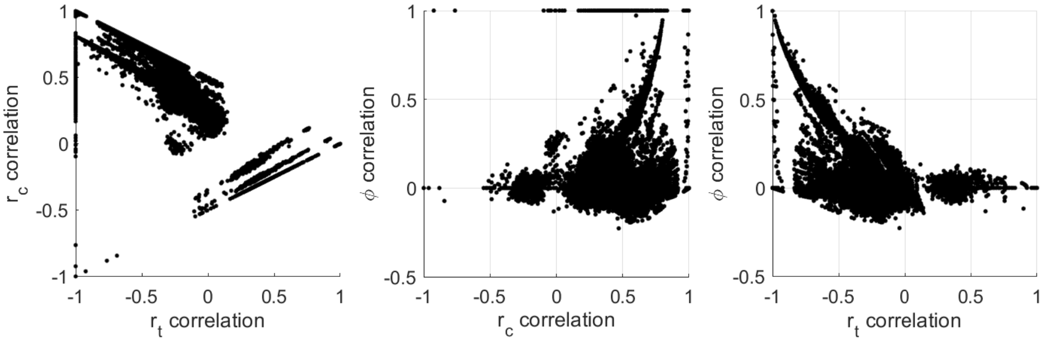
The second metric, r_c, is provided by Equation 8 and describes the balance between the number of concept designs were both items are satisfied (i.e. A) and the number of cases were neither of the items is satisfied (i.e. D). If $r_c > 0$, A is larger than D. The maximum value of $r_c = 1$, meaning that both items are satisfied in all cases. Similarly, $r_c < 0$ if A is smaller than D, and $r_c = -1$ if both items are never satisfied at the same time.

$$r_c = \frac{A-D}{A+B+C+D} \tag{8}$$

Hence, the Utopian point for the two new correlation coefficients is $r_t = -1$ and $r_c = 1$.



(a) Based on 19 parameters in Case study 1.



(b) Based on 739 parameters in Case study 2.

Figure 7: Comparison between the ϕ (Garrett, 1958), and the new r_t and r_c coefficients of correlation. Each dot represents the correlation value between two design parameters across 1000 designs. The left figures show the r_t and r_c correlation for all pairs of design parameters. The middle figures show the ϕ and r_c correlation and the right figures show the ϕ and r_t correlation for the same parameters.

Figure 7a shows the relation between Garrett (1958)'s ϕ, and the new r_t and r_c coefficients of correlation, based on respectively 19 and 739 parameters for 1000 concept designs generated in Sections 3 and 4. The left figures show the relation between r_t and r_c. It clearly shows that many pairs of design parameters can often be met simultaneously ($r_t \approx -1$ and $r_c \approx 1$), or need to be traded off ($r_t \approx 1$ and $r_c \approx 0$). There appears to be a slight negative correlation between r_t and ϕ (right figures). However, there is no clear correlation between r_c and ϕ (middle figures). Therefore, ϕ does provide some information on whether two parameters need to be traded off, but does not provide information on whether two parameters can be met simultaneously. Generally, both the small and large case show similar correlations. Hence, both r_c and r_t, instead of ϕ are used in the remainder of this paper to allow designers to get clear insights into the relation between pairs of design parameters.

2. *Use exploratory filtering*. Although r_c and r_t can be used to inform the designer on the nature of the relationship between pairs of parameters, additional effort is required to identify how larger sets of parameters relate. Indeed, besides dependence between pairs of design parameters, a designer needs to know the dependencies between *all* parameters, for instance to evaluate which combinations of parameters are most restrictive to the design space. A concrete example is the question if all specified global positions can be satisfied in a single concept design, and if not, which global positions cannot be satisfied and why they cannot be satisfied. Eventually, such interactive, exploratory filtering of the design data helps the designer to identify how, when and why design parameters relate, but also to identify potential promising concept designs (Duchateau, 2016).

3. *Generate and analyse selected concept designs*. Studying individual concept designs might yield additional insights into possible solutions to address identified conflicts. Additionally, it might be used to identify which parameters need to be adapted in subsequent iterations (e.g. compartment sizing). Generally, concept designs are less abstract than numerical representations of design data (such as the developed correlation coefficients). Thus, individual concept designs might be of good use during collaborative design sessions, i.e. to identify additional design rationale (DeNucci, 2012) or as a familiar representation of the design (Van Oers et al., 2018).

3 Case study 1 - conceptual demonstration

This section describes a small case study which demonstrates the principle working mechanisms of the allocation method as well as the data exploration process. The case study comprises: 4 compartments with various sizing, 8 systems with various sizing and positioning requirements, and 8 interactions between these systems. This input is visualised in Figure 8. The case study comprises of 19 design parameters (i.e. system size and position, and interactions) in total. Details of the input can be found in the data repository linked in Section 6.

(a) Compartmentisation for Case study 1

(b) Network of systems and interactions. Increasing node size corresponds to increasing system size. Square nodes indicate systems with global position and area requirements, while round nodes represent systems with an area requirement only. Blue and red edges indicate adjacency and separation interactions between connected systems respectively.

Figure 8: Visualisation of input to Case study 1

The available area in the four compartments ($201.6m^2$) is larger than the required area by the eight systems ($185m^2$). The developed method will be used to check whether a feasible distribution of the systems across the compartments is possible.

The required interactions contain one directly conflicting, non-resolvable pair of interactions between systems A and B. The feasibility of either of these interactions and the impact on other design parameters will be evaluated.

To investigate possible allocation configurations the developed method is used to generate a set of 1000 concept solutions. The generation time is in the order of 6 seconds. This indicates that, for small design problems, solutions can be generated in real-time.

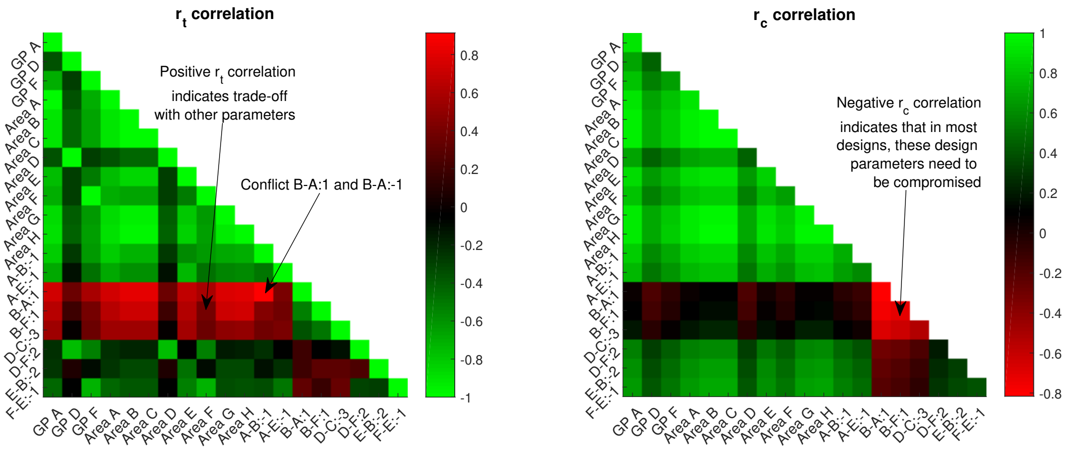
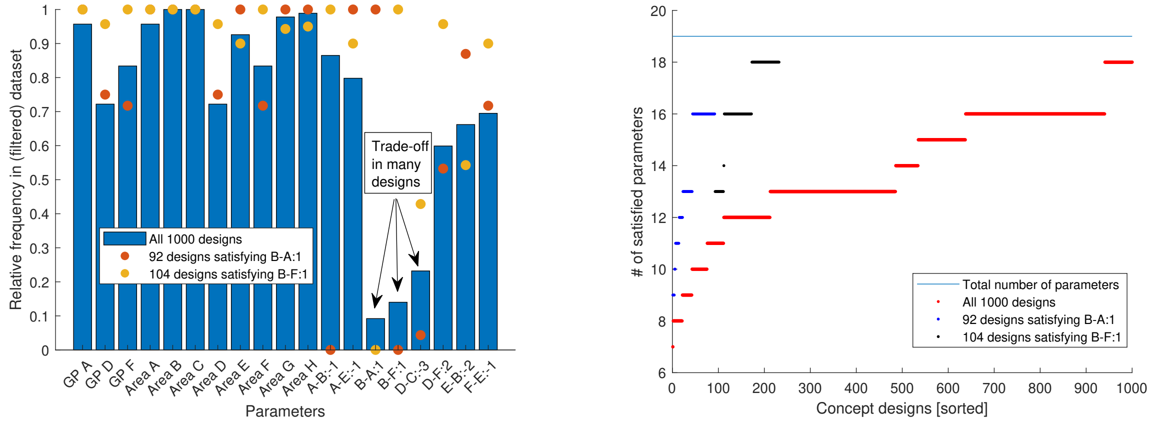


Figure 9: r_t and r_c correlation between 19 design parameters for Case study 1.



(a) Relative frequency of design parameter satisfaction.

(b) Number of design parameters satisfied.

Figure 10: High level results for Case study 1.

Figure 9 shows the r_t and r_c correlation between 19 design parameters. Most design parameter pairs are characterised by a negative r_t and a positive r_c correlation. This means that parameters in these pairs can likely both be satisfied. In contrast, there is a high positive r_t correlation between interactions B-A:1, B-F:1, and D-C:-3 and all other parameters. That is, there is likely a conflict between these parameters and all other parameters. Also, there is a significant negative r_t correlation between these three interactions, i.e. there is a conflict in the designs were these interactions are satisfied, that is, only one of the interactions in each pair is satisfied. Similarly, there is a strong negative r_c correlation between these parameters. That is, in most designs, these three interactions cannot be satisfied, regardless if considered individually (diagonal values) or in pairs (non-diagonal values). This is also shown in Figure 10a, where the length of each bar corresponds to the number of designs in which a design parameter is satisfied. For example, interaction B-F:1 is satisfied in only 14% of the designs.

These two observations indicate that these three interactions are most restrictive for the design space, if these interactions need to be satisfied. Therefore, the consequences of satisfying these interactions is investigated further. For sake of brevity, only interactions B-A:1 and B-F:1 taken into consideration, yet the procedure would be similar for D-C:-3.

As indicated above, there is a conflict between interactions B-A:1 and B-F:1. The interactions require systems A, B, and F to be allocated to the same compartment. However, the total required area for these three systems is $90m^2$, which is larger than any available compartment. Hence, these two interactions can never be simultaneously be satisfied, unless the area requirements are compromised or the available space enlarged.

Although meeting any of these two interactions is a challenge, let's investigate the impact on the design space if B-A:1 and B-F:1 are separately set to be satisfied. Figure 10a shows the relative frequency of design parameter satisfaction for all 1000 designs, as well as for the filtered set satisfying interaction B-A:1 (containing only 92

Interaction format: system x-system y:interaction type designs) and the filtered set satisfying interaction B-F:1 (containing only 104 designs).

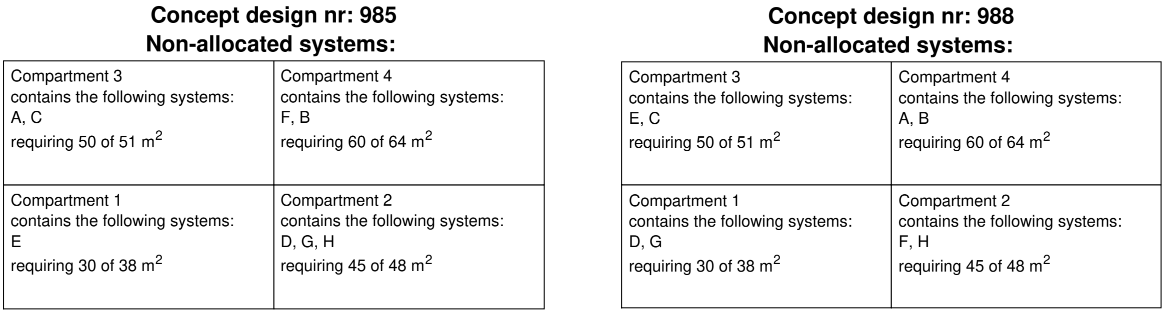
All designs satisfying interaction B-A:1, meet 9 of 19 parameters. Besides the conflict with interaction B-F:1, a conflict with interaction A-B=-1 becomes apparent, since there are no designs satisfying A-B:-1. This conflict can also be noted by the high r_t correlation in Figure 9. Note this was the conflict that was deliberately included in the input. Also, there are still a few designs in which interaction D-C:-3 is satisfied.

All designs satisfying interaction B-F:1, meet 8 of 19 parameters. Generally, selecting B-F:1 seems to be less stricture than selecting B-A:1. This can be seen by the relative position of the data points in Figure 9, where for 13 parameters the relative frequency is equal or higher if B-F:1 is selected.

Figure 10b shows the number of design parameters satisfied for all 1000 designs, as well as for the filtered set satisfying interaction B-A:1 and the filtered set satisfying interaction B-F:1.

- At maximum, 18 of 19 design parameters can be met. This is due to the deliberate (and unsolvable) conflict between interaction A-B:-1 and B-A:1.
- If B-A:1 needs to be satisfied, at maximum 16 design parameters are met, i.e. 3 design parameters cannot be met (amongst one other, interactions A-B:-1 and B-F:1).
- If B-F:1 needs to be satisfied, at maximum still 18 design parameters are met, only interaction B-A:1 needs to be compromised. Hence, the selection for B-F:1 seems to be more promising, and therefore it could be decided to compromise interaction A-B:1.
- The selection of either of these interactions shows also positive trends, e.g. the global position of system D (GP D) is in relative more designs satisfied. In other cases, parameters are relatively less frequent satisfied (e.g. GP F for B-A:1).

Finally, two concept designs are reviewed, which subsequently satisfy interaction B-A:1 (Figure 11b) and B-F:1 (Figure11a). Both designs satisfy the maximum number of satisfied design parameters found for these cases, i.e. 16 and 18 respectively. Based on these two concept designs, the available area in Compartment 1 seems relatively large, compared to Compartment 3. The former has $8m^2$ left, while the latter only has $1m^2$ after allocation of systems.



(a) Layout ID 985, satisfying interaction B-F:1 and 18 parameters in total.

(b) Layout ID 988, satisfying interaction A-B:1 and 16 parameters in total.

Figure 11: Two layouts for Case study 1

Layout ID 985 satisfies all parameters, except for interaction B-A:1. This problem is not resolvable with the current compartment sizing, but can be resolved if a compartment is enlarged to $90m^2$, as explained above.

Layout ID 988 does satisfy interaction B-A:1, but does not satisfy the interactions A-B:-1 (not resolvable), B-F:1 (only resolvable with a sufficiently large compartment), and D-C:-3. The latter interaction requires systems C and D to be separated by a minimum radial distance of 1 compartment. This is not satisfied, since these systems are allocated in adjacent compartments. The most promising solution is to swap systems D and H. This would require compartment 2 to be $50m^2$, which is only $2m^2$ larger than it's current size. Yet, this would keep Layout ID 988 inferior to Layout ID 985, because it would let the other two interactions unsatisfied.

As said above, both designs satisfy the maximum number of satisfied design parameters found by the allocation method. The evaluation of the two selected layouts shows that the allocation method indeed found the maximum *possible* number of satisfied design parameters for this case study.

In practice, concept designs which don't fulfil all requirements might not pass a design review. However, during early stage design, the goal of design work is to get insight into design drivers, feasibility and risk (see also Section 1). From that perspective, non-perfect concept designs (e.g. because of lack of detail, or because not all requirements are met) can still be useful to support the early stage stakeholder dialogue.

Lessons learned

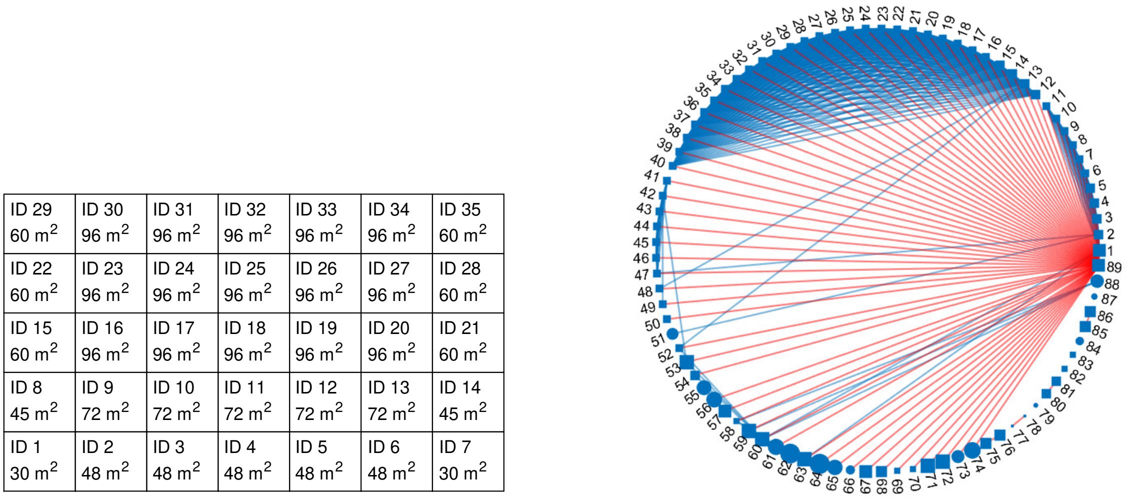
There are three main lessons to be learned from Case study 1. First, the time required to analyse the data is significantly larger than the time required to generate the data. While the generation time is in the order of seconds, one can spend hours on the analysis of the data. One of the main reasons is that the case study had been conducted without a clear starting question. Additional iterations (e.g. to investigate the impact of enlarging a compartment, or the impact of removing one or more unsolvable constraints) will likely be faster due to the more limited scope. During early stage design, such iterations to find design insights are typical (Duchateau, 2016).

Second, understanding the meaning of the new correlation metrics takes time. However, it is likely that training and experience using the metrics will reduce this effort. Also, the new correlation metrics were found to be useful to identify likely conflicts between design parameters.

Thirdly, the generation of the appropriate visualisations takes considerable effort and time. However, these can be reused when other data sets are analysed, as will be observed in Case study 2.

4 Case study 2 - Oceangoing Patrol Vessel

This section describes briefly a full ship size allocation problem, to evaluate if and how large scale allocation problems can be handled by the proposed method. The case study comprises of 35 compartments, 89 systems (comprising 89 area and 75 global position requirements), and 575 interactions. This input is visualised in Figure 12. Details of the input can be found in the data repository linked in Section 6. The list of systems is based on the notional Oceangoing Patrol Vessel (OPV) presented in le Poole et al. (2022b).



ID 29 60 m^2	ID 30 96 m^2	ID 31 96 m^2	ID 32 96 m^2	ID 33 96 m^2	ID 34 96 m^2	ID 35 60 m^2
ID 22 60 m^2	ID 23 96 m^2	ID 24 96 m^2	ID 25 96 m^2	ID 26 96 m^2	ID 27 96 m^2	ID 28 60 m^2
ID 15 60 m^2	ID 16 96 m^2	ID 17 96 m^2	ID 18 96 m^2	ID 19 96 m^2	ID 20 96 m^2	ID 21 60 m^2
ID 8 45 m^2	ID 9 72 m^2	ID 10 72 m^2	ID 11 72 m^2	ID 12 72 m^2	ID 13 72 m^2	ID 14 45 m^2
ID 1 30 m^2	ID 2 48 m^2	ID 3 48 m^2	ID 4 48 m^2	ID 5 48 m^2	ID 6 48 m^2	ID 7 30 m^2

(a) Compartmentisation for Case study 2

(b) Network of systems and interactions. Node size is related to system size. Square nodes indicate systems with global position requirements. Blue edges indicate adjacency interactions. Red edges indicate separation interactions.

Figure 12: Visualisation of input to Case study 2

Table 3 summarises two runs of the allocation method. In the first run 1000 concept designs and in the second run 50 concept designs were generated. What is clear, is the difference in required calculation time, as well as accuracy. In contrast to the first run, the second run might be representative for interactive design work from the perspective of calculation time. However, does the reduction of accuracy also yield a reduction of insight into constraining design parameters?

Table 3: Summary of results for Case study 2

	Run 1	**Run 2**
Number of concept designs	1000	50
Calculation time [s]	209	14
Maximum number of parameters met	678	644
Percentage of total number of parameters (739) [%]	92	87

This seems not to be the case. Indeed, Figure 13 shows the relative frequency of design parameter satisfaction

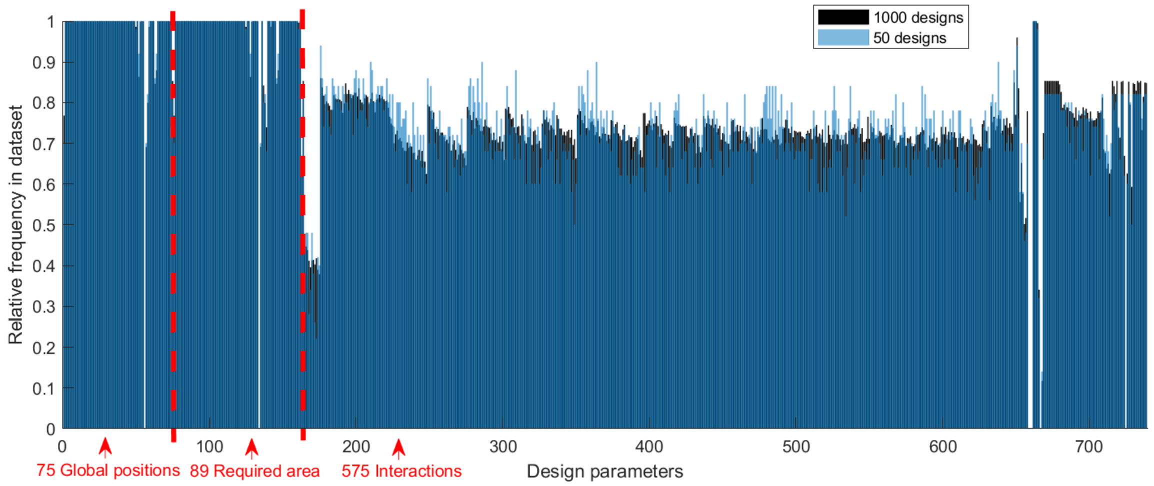
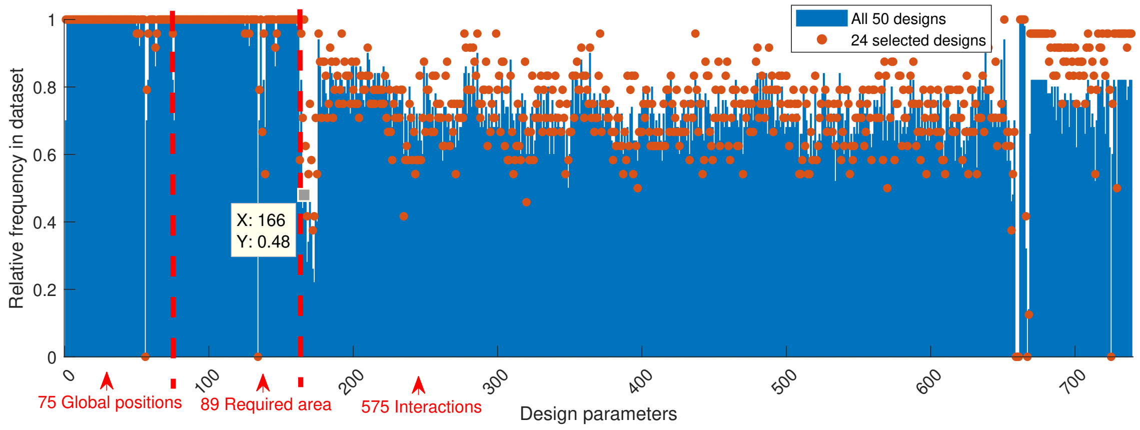
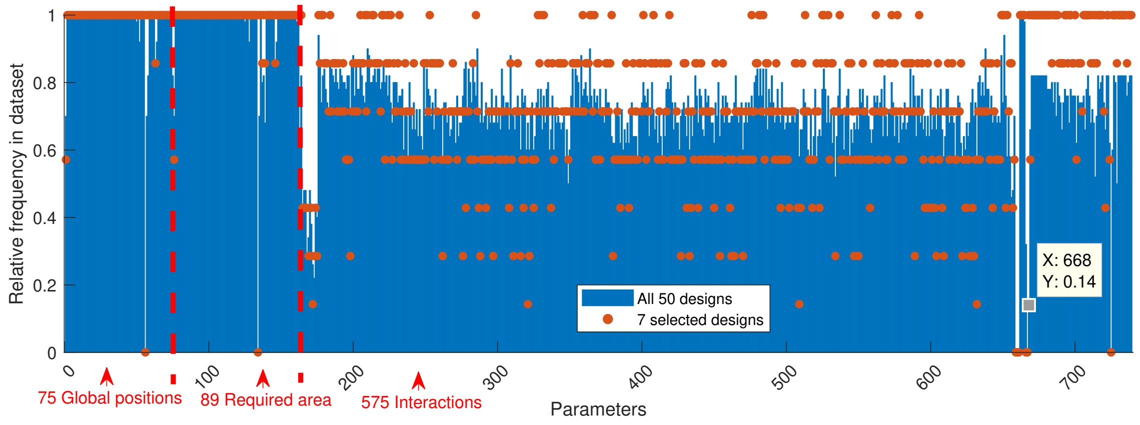


Figure 13: Relative frequency of design parameter satisfaction for Case study 2, for 1000 and 50 designs. For sake of readability, the parameters haven't been labelled.



(a) Design parameter 166: interaction Commanders Cabin - 1 person Officers cabin:2



(b) Design parameter 668: interaction Waste store - Mess:1

Figure 14: Impact of two design parameters on design space. Grey box indicates relative frequency of selected parameters. Orange dots indicate relative frequency in filtered design space.

for Case study 2 for both runs. Assuming the first run is most accurate, Figure 13 clearly shows for which parameters the second run overestimated (light blue bar is visible) or underestimated (black bar is visible) the satisfaction of design parameters. Although there are differences, the overall trend for each design parameter corresponds between the two runs. Hence, this is an indication that faster, lower accuracy models might be used (although carefully) as a basis for collaborative design decision-making.

Next, the impact of two design parameters on the design space is evaluated. The two selected design parameters are 166 (interaction Commanders Cabin - 1 person Officers cabin:2) and 668 (interaction Waste store - Mess:1). The filtered design space for these interactions is shown in Figures 14a and 14b respectively. Some of the observations that can be made are:

1. Selecting parameter 668 yields the largest reduction of the design space, to 7 designs. Parameter 166 yields 48% of the original design space.
2. The spread in design parameter satisfaction is larger for parameter 668 than for parameter 166.
3. There is no direct conflict between these two parameters, since both filtered sets contain designs that still satisfy the other parameter.

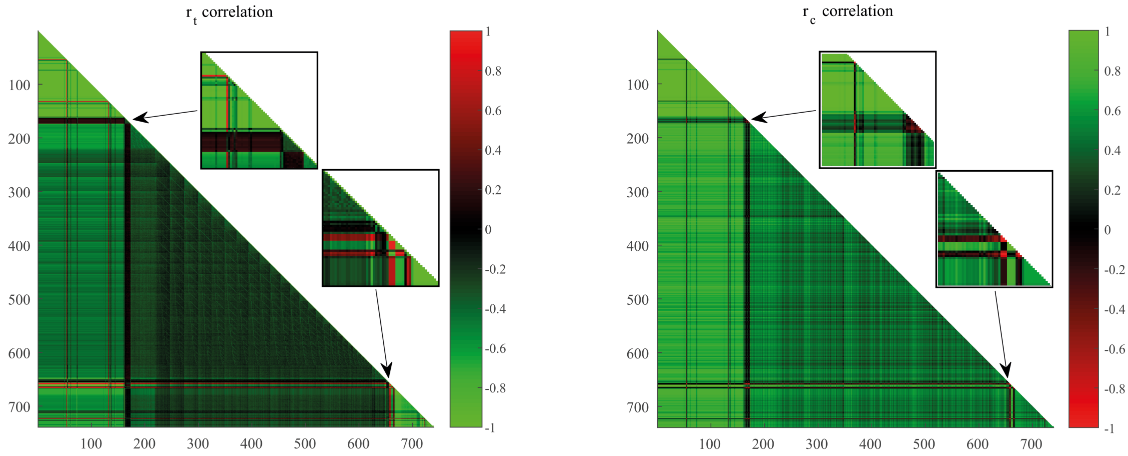


Figure 15: r_t and r_c correlation between 739 design parameters for Case study 2.

Figure 15 shows the r_t and r_c correlation between the design parameters in Case study 2. The insets show more detailed views on particular parts of the design space. What stands out from the overall correlation map is the correspondence with Figure 14. For instance, areas where $r_t \approx 1$ and $r_c \approx -1$ (i.e. visible line patterns) coincide with low relative frequency areas in Figure 14. This gives confidence that the new correlation metrics are also applicable for more elaborate design problems.

Figure 16 shows the one of the generated concept designs in Case study 2. Such allocation of systems might be used by a naval architect as a starting point for the further development of a detailed General Arrangement Plan, or be used in WARGEAR to automatically generate a 2D layout plan.

Lessons learned

There are three lessons to be learned from Case study 2. First, setting up the design problem requires significant effort. In the context of real-time collaborative design sessions this is not expected to be a major issue. Indeed, designers will likely prepare models etc. prior to the sessions (Bandecchi et al., 2000). It has been seen that the time required for generation of concept designs is still relatively low, which indicates that automated design tools might be useful, even for large design problems.

Second, the new correlation metrics provide results in line with other data derived from system allocation. However, the metrics do not provide insight into the extent that parameters are met. For instance, can a system, which currently cannot be allocated, be allocated with 95% of its currently required area? Currently, these variations are not evaluated in the allocation process. Instead, the designer is required to alter the input to investigate such questions.

Third, the availability of the visualisations in Case study 1, led to a perceived decrease in time and effort required for analysing the substantial larger data set obtained in Case study 2. More elaborate use of dedicated data exploration tools might help to get easier insight into the vast amount of data produced in the allocation process.

5 Conclusion

The wicked nature of early stage naval ship design requires a process of requirements elucidation. Such requirements elucidation takes place in a stakeholder dialogue, in which requirements and concept designs are discussed

Compartment 29 contains the following systems: Intel room, NBCD filter rooms requiring 17 of 60 m^2	Compartment 30 contains the following systems: Officers cabins , Engineering office, HVAC rooms requiring 84 of 96 m^2	Compartment 31 contains the following systems: Officers cabins , Officers cabins , Workshop mechanical and welding, Workshop electrical requiring 89 of 96 m^2	Compartment 32 contains the following systems: Dayroom officers, Medical area requiring 52 of 96 m^2	Compartment 33 contains the following systems: Officers cabins, Radio central, Briefing room requiring 68 of 96 m^2	Compartment 34 contains the following systems: Computer room, Main switchboard requiring 96 of 96 m^2	Compartment 35 contains the following systems: Sanitary & showers , Fresh water maker 1 requiring 22 of 60 m^2
Compartment 22 contains the following systems: Meeting room requiring 48 of 60 m^2	Compartment 23 contains the following systems: Officers cabins , Officers cabins , Officers cabins , Compass room, Fresh water maker 2 requiring 67 of 96 m^2	Compartment 24 contains the following systems: Officers cabins, Dry stores requiring 86 of 96 m^2	Compartment 25 contains the following systems: Officers cabins, Fitness room, Baggage storage, Fire fighting room requiring 68 of 96 m^2	Compartment 26 contains the following systems: Command central requiring 96 of 96 m^2	Compartment 27 contains the following systems: Commanders Cabin, Officers cabins , NBCD filter rooms requiring 75 of 96 m^2	Compartment 28 contains the following systems: Bridge requiring 60 of 60 m^2
Compartment 15 contains the following systems: Chiller unit aft requiring 20 of 60 m^2	Compartment 16 contains the following systems: Rating cabins, Computer room requiring 78 of 96 m^2	Compartment 17 contains the following systems: Rating cabins, Dayroom petty officers requiring 70 of 96 m^2	Compartment 18 contains the following systems: Petty officers cabins, Petty officers cabins, Petty officers cabins requiring 42 of 96 m^2	Compartment 19 contains the following systems: Petty officers cabins , Petty officers cabins, Petty officers cabins, Petty officers cabins, Petty officers cabins, Petty officers cabins requiring 85 of 96 m^2	Compartment 20 contains the following systems: Petty officers cabins , Petty officers cabins, Petty officers cabins, Petty officers cabins, Petty officers cabins, Compass room requiring 83 of 96 m^2	Compartment 21 contains the following systems: Petty officers cabins , Petty officers cabins, Petty officers cabins, Petty officers cabins requiring 57 of 60 m^2
Compartment 8 contains the following systems: Rating cabins, Emergency switchboard requiring 20 of 45 m^2	Compartment 9 contains the following systems: Mess requiring 67 of 72 m^2	Compartment 10 contains the following systems: requiring 0 of 72 m^2	Compartment 11 contains the following systems: Petty officers cabins, Rating cabins, Sanitary & showers , Laundry requiring 68 of 72 m^2	Compartment 12 contains the following systems: Petty officers cabins, Petty officers cabins, Petty officers cabins requiring 42 of 72 m^2	Compartment 13 contains the following systems: Petty officers cabins , Petty officers cabins, Petty officers cabins, Petty officers cabins, Petty officers cabins requiring 71 of 72 m^2	Compartment 14 contains the following systems: Petty officers cabins, Petty officers cabins, Hydrophore requiring 38 of 45 m^2
Compartment 1 contains the following systems: Rating cabins, Bakey requiring 21 of 30 m^2	Compartment 2 contains the following systems: Rating cabins, Main switchboard requiring 42 of 48 m^2	Compartment 3 contains the following systems: Engine room requiring 48 of 48 m^2	Compartment 4 contains the following systems: requiring 0 of 48 m^2	Compartment 5 contains the following systems: Rating cabins, Sanitary & showers requiring 25 of 48 m^2	Compartment 6 contains the following systems: Dayroom rating, HVAC rooms requiring 42 of 48 m^2	Compartment 7 contains the following systems: Chiller unit forward requiring 20 of 30 m^2

Figure 16: Example of allocation of systems to compartments in Case study 2 (Layout ID 942).

with respect to technical and financial feasibility and risk. Collaborative design processes, such as concurrent design, are aimed at aligning stakeholders through collaborative design decision-making. Current design tools are tailored towards more traditional design review sessions, and might therefore be unsuitable for real-time, collaborative design work.

This paper aimed to investigate how design tools for ship layout design can be used in a real-time manner. That is: 1) how can such tools be used to generate concept designs in real-time, and 2) how can these concept designs be analysed in real-time? As an example problem, the allocation of systems to compartments was considered. An existing allocation method, WARGEAR, was extended and adapted. To support designers in identifying conflicts, and hence necessary trade-offs, between design parameters, a new two-item correlation metric was developed.

Based on two case studies, the calculation time or accuracy of the allocation method does not seem to be the main issue for collaborative design decision-making. Most effort is required for the analysis of the data - which is not a problem for real-time collaborative design as such, but needs to be considered when selecting tools and methods for such design sessions. However, it is beneficial to use design tools with a specific goal or inquiry in mind, as this will enhance the search for insights into the design space. Hence, the development of interactive data exploration and decision tracing seems to be promising and essential research directions to support collaborative design decision-making.

6 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, as well as detailed tests of the method presented in the paper can be found in the following repository: `https://doi.org/10.4121/20141636`. 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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References

Andrews, D., 2011. Marine requirements elucidation and the nature of preliminary ship design. International Journal of Maritime Engineering 153.

Andrews, D., 2018. The sophistication of early stage design for complex vessels. Transactions of the Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering , 1–54.

Andrews, D., Dicks, C., 1997. The building block design methodology applied to advanced naval ship design, in: Proceedings of the International Marine Design Conference, Newcastle, United Kingdom, pp. 3–19.

Bandecchi, M., Melton, B., Gardini, B., Ongaro, F., 2000. The ESA/ESTEC concurrent design facility. Proceedings of EUSEC 9, 2000.

Brown, D., 1986. Defining a warship. Naval Engineers Journal 98, 31–40.

Carlson, C., Fireman, H., 1987. General arrangement design computer system and methodology. Naval Engineers Journal 99, 261–273.

De Bruijn, J., Ten Heuvelhof, E., 2008. Management in networks: on multi-actor decision making. Routledge.

DeNucci, T., 2012. Capturing Design: Improving conceptual ship design through the capture of design rationale. Ph.D. thesis. Delft University of Technology.

Duchateau, E., 2016. Interactive evolutionary concept exploration in preliminary ship design. Ph.D. thesis. Delft University of Technology.

Feadship, 2017. Feadship launches Concurrent Design Feadship (CDF). `https://www.feadship.nl/news/feadship-launches-concurrent-design-feadship-cd-f`. Accessed: 2020-11-04.

Garrett, H.E., 1958. Statistics in psychology and education.

Gaspar, H.M., Brett, P.O., Ebrahim, A., Keane, A., 2014. Data-driven documents (d3) applied to conceptual ship design knowledge. Proceedings COMPIT 2014 .

Gillespie, J., 2012. A Network Science Approach to Understanding and Generating Ship Arrangements in Early-Stage Design. Ph.D. thesis. University of Michigan.

Lipowski, A., Lipowska, D., 2012. Roulette-wheel selection via stochastic acceptance. Physica A: Statistical Mechanics and its Applications 391, 2193–2196.

Medjdoub, B., Yannou, B., 2000. Separating topology and geometry in space planning. Computer-aided design 32, 39–61.

Nick, E., 2008. Fuzzy Optimal Allocation and Arrangement of Spaces in Naval Surface Ship Design. Ph.D. thesis. University of Michigan.

NIDV, 2022. DMO en TNO investeren in een Concurrent Design Facility. `https://www.nidv.eu/nieuws/dmo-en-tno-investerenin-een-concurrent-design-facility-cdf/`. Accessed: 2022-03-28.

le Poole, J., Charisi, N., Droste, K., Habben Jansen, A., Kana, A.A., 2022a. The design knowledge management square - a framework for early stage complex ship design, in: The 15th International Symposium on Practical Design Of Ships And Other Floating Structures (PRADS).

le Poole, J., Duchateau, E., Hopman, H., Kana, A.A., 2022b. On-the-fly design rationale to support real-time collaborative naval ship layout design, in: 14th International Marine Design Conference (IMDC).

le Poole, J.J., Duchateau, E.A.E., Van Oers, B.J., Hopman, J.J., Kana, A.A., 2022c. WARGEAR: 'real time' generation of detailed layout plans of surface warships during early stage design. Ocean Engineering 250, 110815.

Roberts, N., 2000. Wicked problems and network approaches to resolution. International public management review 1, 1–19.

Stevens, A.P., 2016. Naval ship preliminary arrangements for operability and reduced vulnerability. Master's thesis. Virginia Tech.

Takken, E., 2009. Concept Design by using Functional Volume Blocks with variable Resolution. Master's thesis. Delft University of Technology.

Van Oers, B., 2011. A packing approach for the early stage design of service vessels. Ph.D. thesis. Delft University of Technology.

Van Oers, B., Takken, E., Duchateau, E., Zandstra, R., Cieraad, S., van den Broek-de Bruijn, W., Janssen, M., 2018. Warship Concept Exploration and Definition at The Netherlands Defence Materiel Organisation. Naval Engineers Journal 130, 63–84.