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A CASE STUDY INTO AN AUTOMATED DETAILED LAYOUT GENERATION APPROACH IN EARLY STAGE NAVAL SHIP DESIGN

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Synopsis

The Defence Materiel Organisation (DMO) of the Netherlands Ministry of Defence identified that detailing warship layouts to space level of detail during the concept definition design phase is a complex and time consuming process. Currently it can take up to 150 man hours to complete a feasible general arrangement plan (GAP). Yet, these GAPs are crucial for balancing requirements and budget with technical feasible designs. Insufficient consideration of spatial details during concept definition increases the probability that sizing and integration issues will emerge later in the design process.

This paper discusses the first steps undertaken to integrate a new layout generation tool, called WARGEAR (WARship GEneral ARrangement), into the DMO ship design process. WARGEAR is able to semi-automatically generate feasible and balanced detailed layouts in a matter of minutes, thus providing almost real-time feedback and design insight to naval architects. In this paper the issues of tool validation and user acceptance are addressed via a realistic warship design test case and a presentation of the test case results to a larger group of naval architects and senior management at the DMO respectively.

The test case showed that WARGEAR is able to generate detailed layouts that compare well to GAPs manually generated by naval architects. The attendees at the presentation were generally positive, but also provided valuable feedback for further development of the WARGEAR tool and methodology. This shows the potential of WARGEAR to increase the speed of detailed layout generation to a matter of minutes and to improve the early stage design process by providing early insight into detailed layouts and their design drivers.

Keywords: Layout design; general arrangements; optimisation; early stage design; warship design; WARGEAR

1 Introduction

Most naval ships are considered to be space critical, which means their size and costs are governed by spatial requirements (DeNucci, 2012; Carlson and Fireman, 1987). To ensure these spatial requirements are consistent, do not conflict, and can be met with technically feasible and affordable concept designs, the development of layouts during early stage warship design is essential (DeNucci, 2012; Van Oers et al., 2018; Le Poole et al., 2019). For this reason the Defence Materiel Organisation (DMO) of the Netherlands Ministry of Defence generates concept designs with various levels of detail to inform decision-makers as well as to ensure requirement feasibility for future warships (Van Oers et al., 2018).

During early stage design the stakeholder dialogue is essential to define the appropriate set of requirements, i.e. ensuring ‘the right ship is build’ (Van Oers, 2011; Andrews, 2012). During detailed design stages the focus is on ensuring ‘the ship is build right’. The right set of requirements maximises the probability that a fit-for-purpose design solution can be developed and that it will satisfy stakeholders to the maximum extent possible. Therefore it is necessary to investigate the stakeholder’s preferences, as well as to assess the technical and financial feasibility of requirements by developing concept designs. By means of a dialogue about the requirements and the corresponding design implications, a mutual understanding of requirements and their impact is established among stakeholders (Andrews, 2011).

However, it is difficult to assess the implications of requirements. Indeed, requirements are often interrelated as well as conflicting or competing, and efforts to solve design problems may reveal or even create other problems. To solve this ‘wicked problem’ complex ship design is highly iterative (Andrews, 2012; Shields et al., 2016). Hence,

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Author’s biographies

Ir. Joan le Poole holds the current position of Young Researcher at the Delft University of Technology and has the lead in the WARGEAR project. Also, he is a PhD candidate in the field of early stage naval ship design. He completed his Bachelor and Master studies in Marine Technology at the same university in 2016 and 2018 respectively.

Dr. Ir. Etienne Duchateau holds the position of Naval Architect at the Maritime Systems Division of the DMO. He is involved in design tool development and concept exploration studies for future replacement and new building projects of the Royal Netherlands Navy. In 2011 he graduated as Naval Architect at Delft University of Technology. In 2016 he obtained his PhD also at Delft University of Technology for his research on an interactive steerable concept exploration tool for early stage ship design.

Dr. Ir. Bart van Oers has a PhD in Ship Design (2011) and a MSc. in Ship Hydrodynamics (2005) from Delft University of Technology. He works for the Maritime Systems Division of the Netherlands Defence Materiel Organisation since 2009. Bart co-chaired the NATO Research Task Group AVT-RTG-238, and was involved in the Maritime Countermeasures Project at the European Defence Agency. As a team leader, he currently is responsible for conducting concept studies for future warships for the Royal Netherlands Navy.

Dr. Austin Kana is an Assistant Professor in the Department of Maritime and Transport Technology at Delft University of Technology, and is the daily supervisor of Joan le Poole. His research focuses on developing design methods and tools to help address complex ship design problems. He received in PhD in Naval Architecture and Marine Engineering at the University of Michigan in 2016.

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during requirements elucidation concept designs developed by naval architects should support the understanding of the requirements and their design impact. Therefore concept designs should be informative, have an appropriate level of detail, and should trigger stakeholders to express their (updated) design preferences. Consequently, early stage design tools and methods should support naval architects in their efforts to develop the appropriate concept designs and obtain the required design insights.

At the DMO various (semi-)automated design tools are used by naval architects to develop these concept designs (Van Oers et al., 2018; Van Oers, 2011; Takken, 2009). Nonetheless, high level of detail General Arrangement Plans (GAPs) are still manually developed to ensure that spatial and layout requirements can be met. Manually creating a feasible GAP requires significant effort and currently may take up to 150 man hours to complete (Le Poole et al., 2019). However, to accelerate the generation of feasible warship concept designs, insights into sizing and integration problems via high level of detail layouts, should be available without substantial effort. To reduce the effort required to generate these GAPs, the DMO is collaborating with the Delft University of Technology in the WARGEAR (WARship GEneral ARrangement) project (Le Poole et al., 2019). In this project a tool is being developed to support the DMO's naval architects with the generation of GAPs during the concept definition design phase. A more detailed background on the project can be found in Le Poole et al. (2019).

This paper addresses the first steps undertaken to integrate the WARGEAR tool into the DMO design process. Integration of a new tool into an existing process is non-trivial, as it requires the following two steps to be taken: (1) validation and (2) user acceptance. Peffers et al. (2007) describe these steps by demonstration, evaluation, and communication activities.

1. Validation of design tools and methods is difficult, yet important (Andrews, 2012; Peffers et al., 2007; Pedersen et al., 2000). To validate WARGEAR, the tool has been used in a realistic warship design test case, in which GAPs developed by naval architects were compared with layouts generated by WARGEAR.

2. User acceptance requires the careful consideration of the tool's limitations as well as informing future users about the tool's capabilities. The validation test case provided insight in the tool's limitations. A presentation of the results of the test case mentioned in step 1. to a larger group of naval architects and senior management at the DMO was used to build confidence among future users as well as to elicit concerns and questions.

The remainder of this paper is structured as follows. The Section 2 will elaborate on the WARGEAR method and its envisioned integration in the DMO design process. Subsequently the test case and user acceptance presentation are introduced and elaborated in Section 3. The paper closes with conclusions and an outlook to future research.

2 Method and Envisioned Integration

2.1 WARGEAR method advancements

WARGEAR was developed in line with the above statements, and is specifically aimed at aiding naval architects in creating feasible and detailed layout plans for these concept designs (Le Poole et al., 2019). As mentioned in the introduction, WARGEAR has been developed to generate 'detailed layouts' based on a predefined 'functional arrangement', which consist of several 'functional blocks'. Such functional arrangements are generated by DMO naval architects in the FIDES tool (Van Oers et al., 2018; Takken, 2009), and provide the major structural and functional subdivision of the ship. An example of a functional arrangement is shown in Figure 1. Further, naval architects provide a list of spaces to be arranged in the functional arrangement to WARGEAR, as well as an allocation of these spaces to specific functional blocks. This allocation can be very rough, e.g. space X can be arranged in each functional block, or very specific, e.g. space Y should be arranged in functional block Z. Note that a compartment specific allocation is not always possible, as functional blocks can overlap multiple compartments, see also Section 3.2. The specified allocation is then used by the code to allocate spaces to compartments, such that the total area of the spaces is less or equal to the area of the compartment these spaces are allocated to.

Since the initial paper, several changes to the underlying mechanics of WARGEAR have been implemented. These changes have resulted in (1) a reduction in the calculation time, (2) a reduction of the resulting number of layouts, and (3) a significant improvement of the quality of the layouts.

1. The initial requirement for calculation time for WARGEAR was twelve hours, enabling overnight calculations (Le Poole et al., 2019). Additional time is required to generate input for WARGEAR as well as to analyse the resulting detailed layouts. Advances in the code now require approximately fifteen minutes to complete the generation of 800 detailed layouts, compared to 11 hours to generate more than 200,000 layouts in (Le Poole et al., 2019).

2. The reduction of the number of generated layouts is caused by a reduction in the convergence time for the optimiser due to advances in the code, i.e. less layouts need to be generated to obtain sufficiently good

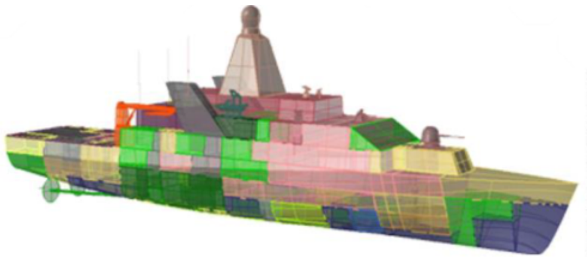

Figure 1: An example of a functional arrangement as generated in FIDES (Van Oers et al., 2018).

results. Besides reducing the calculation time, the reduction of number of resulting layouts also reduces the time required for analysis. Instead of waiting for overnight calculations, the code can now be used in a near-real-time, iterative way, thus increasing the speed at which design insight can be gained.

3. Some of the issues initially raised on the feasibility of the layouts Le Poole et al. (2019) have been addressed[1]:

    - Passageway routing: To improve realism of the passageway routing, the main passageways are now added to the functional arrangement by the naval architect.
    - Staircase placement: A few general rules have been added to WARGEAR to improve staircase placement, based on the functional arrangement.
    - Space arrangement: The speed of space arrangement has been significantly increased by adapting a different space arrangement method.
    - Local connectivity: The pre-space arrangement connectivity method in Le Poole et al. (2019) proved too restrictive for space arrangement. To solve this issue, a post-arrangement connectivity method has been developed based on Marson and Musse (2010).

    As a result, detailed layouts are now more realistic, which contributes to the insight that can be gained from these layouts. An example of a detailed layout generated by WARGEAR is given in Section 3.1.2. In fact, layouts generated in Le Poole et al. (2019) could barely inform naval architects on the required area for space connectivity, although providing such insight is a key requirement for WARGEAR. Consequently, naval architects should be able to gain more confidence in the feasibility of functional arrangements, and thus inform decision makers with higher confidence whether the functional arrangement is sufficiently sized to accommodate all required spaces.

These changes have necessitated a need to change the design process around detailed concept design generation.

2.2 WARGEAR integration in DMO design process

As mentioned in Section 1, the aim of the WARGEAR project is to reduce the effort required for detailed layout generation. Now the resulting tool is sufficiently developed to quickly generate layouts which are convincing and informative (see Le Poole et al. (2019) and Section 2.1) the integration between FIDES and WARGEAR in the DMO design process needs to be formalised.

In Figure 2 both the current and future process integration between the design tools FIDES (Takken, 2009), the 3D-CAD tool Rhinoceros, and WARGEAR are visualised. The solid arrows represent the current process, while the dashed arrows indicate the information flow in the future process.

Current process

In the current design process at the DMO, validation of the functional arrangement is done via GAP generation in the 3D-CAD tool Rhinoceros. The functional arrangement and GAP also provide input to the stakeholder dialogue. The level of GAP development depends on the procurement project. Thus, a GAP will not be generated for all concept designs or all ship design projects. However, this reduces the confidence naval architects have on the feasibility of spatial requirements. Since the effort required for GAP generation is significant, this task is often postponed due to capacity limitations, and therefore sizing and integration issues are typically identified later in the design phase (Le Poole et al., 2019).

Future process

Naval architects can use WARGEAR to validate the functional arrangement and to identify spatial integration issues, as well as to investigate various detailed layout configurations and their design implications. Since WARGEAR

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[1] A future paper will address these changes and the mathematical mechnanics of the code in more detail.

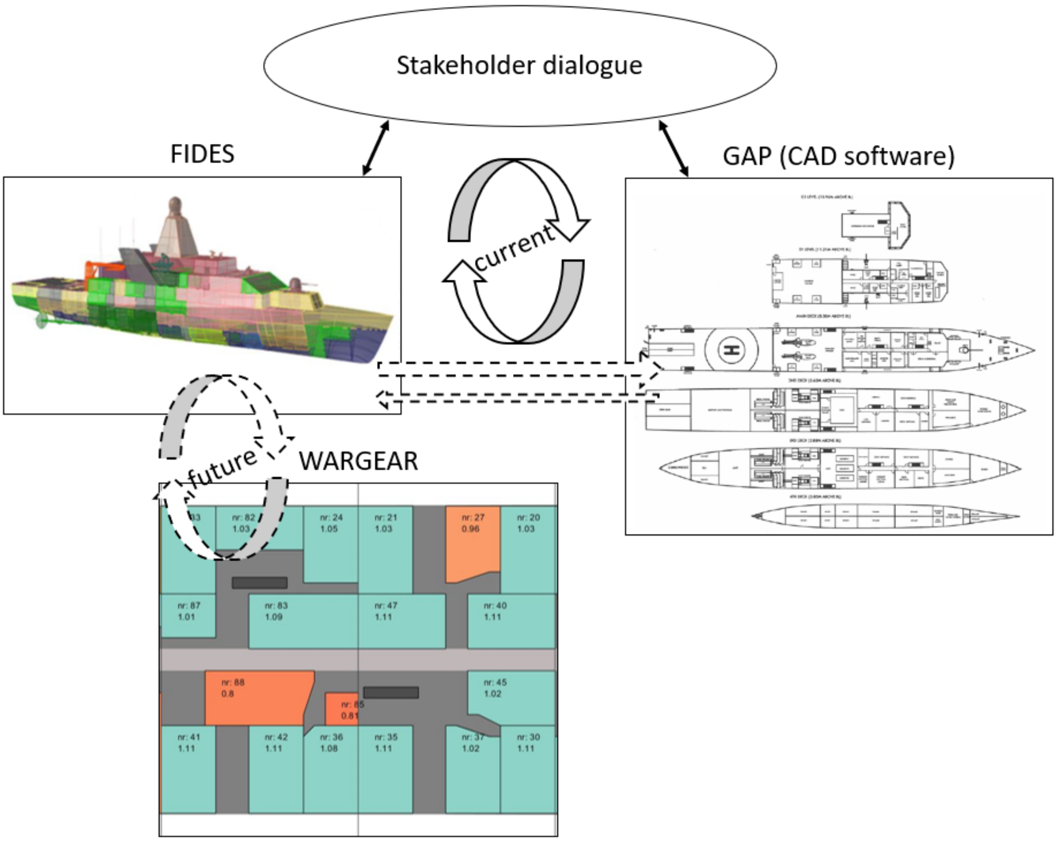

Figure 2: Solid and dashed arrows respectively indicate current and future information flow between FIDES, Rhinoceros, and WARGEAR. Figures derived from Van Oers et al. (2018) and Rigterink (2014).

is able to quickly provide naval architects with visual and textual information on achieved space size and arrangement, WARGEAR can be used in any ship design project. If the functional arrangement is sufficiently developed and validated using WARGEAR, naval architects can start working on a GAP. The GAP will primarily provide input for the stakeholder dialogue in the future process. However, spatial integration issues might still emerge during the GAP generation. Therefore a feedback loop to the functional arrangement will still be in place, although less prominent than in the current process.

3 Case study

As mentioned in the introduction, as part of the WARGEAR project a test case at DMO was performed. This section will focus on this first test case of WARGEAR at the DMO, aimed at tool validation and user acceptance. Therefore this test case consists of the following two parts.

1. **Test case 1: Design review**. The workflow and tool were tested on a realistic warship design case. In Section 3.1 insight will be given into the type of questions WARGEAR can answer. Also, feedback from naval architects on the results will be elaborated on.

2. **Test case 2: WARGEAR introduction**. A comprehensive presentation of the tool, why it has been developed, its working mechanism, and the envisioned use in the design process of future naval vessels, has been given to several naval architects and senior management at the DMO. Also, feedback from this session has also been recorded and will be discussed in Section 3.2.

3.1 Test case 1: Design review

3.1.1 Context

For a warship design project at the DMO, naval architects were asked to give insight into the possible feasible manning decompositions and the options for feasible accommodation standards for a fixed functional arrangement. The manning decomposition comprises the number of officers, non-commissioned officers (NCO) and ratings to be accommodated in the ship. Following from the manning decomposition is a list of required cabins and corresponding cabin sizes. Depending on the accommodation standard, the required cabin size can be reduced by separating sanitary spaces from the cabins into shared sanitary blocks. On the one hand, this will increase the number of spaces to be arranged, since the space list contains not only various cabins, but also the sanitary blocks. On the other hand, separating sanitary spaces from cabins might lead to a feasible arrangement of spaces, when larger cabins with a higher accommodation standard cannot be arranged, depending on the overall layout of the vessel and the available area and shape of the available area. In Figure 3 this breakdown of choices to be made is summarised.

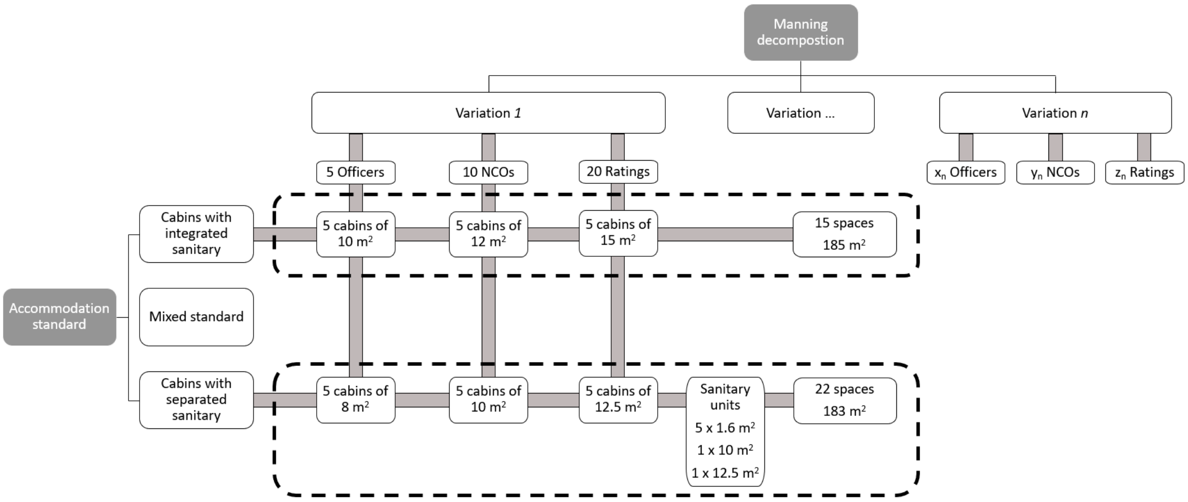

Figure 3: Simplified breakdown of the design variations for Test Case 1. Note that numbers are indicative. The dashed boxes show the spaces resulting from different accommodation standards for the same manning decomposition.

In the current design process, as described in Section 2.2, naval architects have to spend significant effort to investigate the feasibility of the various manning compositions and accommodation standards. Ideally, multiple different GAPs are developed to investigate the different options and to better support the stakeholder dialogue. However, due to capacity limitations, only a few variations can be studied in detail by the naval architects. For this test case the GAPs generated by the naval architects were used to validate the WARGEAR tool and thus to increase the confidence in the tool at the DMO.

In order to produce the required input for WARGEAR, one of the naval architects, who has approximately four years of experience in naval ship design and who had worked on the design project, was consulted. This led to clear insight into the variations of manning compositions and accommodation standards to study. After preparing the code to handle the specific functional arrangement, approximately 15-30 minutes were required to produce the space list for the first variation. This space list was already partially available from the standard design process. For each variation, WARGEAR needs approximately 15 minutes to complete the calculations. With an additional 15-30 minutes to review the produced detailed layouts, the total time required to complete one variation is approximately 1 to 1.5 hours. In total eight variations were studied in a period of two days. This is significantly less than the time required by naval architects to find whether a certain manning decomposition and accommodation standard fits into the design. Note that naval architects still have to develop a GAP, but with the additional insight gained by the WARGEAR study naval architects have a better starting point with regards to both the probable feasible manning decomposition and accommodation standards, as well as a rough feasible arrangement of spaces in the ship. The insight provided by WARGEAR can be used to better define spatial requirements earlier in the design process. WARGEAR can be used to assess whether spatial requirements, e.g. requirements for manning decomposition and accommodation standards, are feasible from a technical point of view to inform decision makers and, if necessary, to challenge requirements. The main purpose of WARGEAR, however, is to inform the naval architects, such that they are better informed in the stakeholder dialogue.

As mentioned above, the naval architects had already developed insight into the possible feasible manning configurations, and had developed a GAP for the design case. Therefore, the WARGEAR results of some of the variations could be compared to the naval architect's efforts. The detailed layouts generated by WARGEAR compared well to the existing GAP at various points, which gave confidence that naval architects could use the detailed layouts as a starting point for GAP development in future design tasks. The following three observations could be made.

1. The naval architects were able to arrange cabins in such a way that all furniture would fit, but not all cabins would meet their required area. Since WARGEAR is not able to arrange furniture inside cabins, only the area of spaces between the detailed layout and the GAP could be compared. Like the naval architect, WARGEAR was able to arrange all spaces, but not in regards to their required area. In fact the difference between the total arranged area by naval architects and WARGEAR was minimal: WARGEAR was able to arrange an additional $7m^2$, which is less than 1% of the total arranged area.

2. Although WARGEAR was able to arrange slightly more square meters, the cabin sizes in the existing GAP were more balanced. Indeed, some of the cabins in the detailed layout were clearly too small to fit all furniture, while most cabins met their required size or were slightly larger[2].

3. WARGEAR only arranges rectangular spaces, whereas naval architects can use more creativity and elaborate shapes, such as L-shapes, to make more efficient use of available area.

3.1.2 Example compartment arrangement

In Figure 4a a representative section of a larger detailed layout generated by WARGEAR is given. The figure shows two compartments on one deck, a T-shaped passageway, three staircases, and several arranged spaces. Most spaces have met their required area (RA), i.e. the achieved area (AA) is larger than or equal to the RA, which is indicated by the green colour. Some spaces have not met their area requirement, which is indicated by the red colour shades. The total quality of layout j is assessed using Equation 1, which is to be minimised (Le Poole et al., 2019). Further the layout is assessed by visual inspection by naval architects.

$$A_j = \sum_{i=1}^{n_{space,j}} \max(0, RA_i - AA_i) \tag{1}$$

Spaces are allocated to these compartments based on the required area and the available area in each compartment. The available area is defined as the total area in a compartment minus the area used by passageways and staircases. Therefore spaces should theoretically fit from an area point of view. However, not all spaces meet their required area, due to two reasons:

- The two staircases in the aft compartment have been placed separated from the passageway, which is caused by the arrangement of spaces on a lower deck. The arrangement of staircases resulted in a restricted and irregular shaped positioning matrix, in which not all cabins can be arranged properly, e.g. space 40 and 42.
- To connect all spaces and staircases with the main passageway, WARGEAR reserves area to construct local passageways to ensure space connectivity, e.g. from space 14, 29, 33, and 45. Space 14 and 45, for instance, do not meet their area requirement because of this effect.

Naval architects might consider removing one of the staircases in the aft compartment to create additional area for spaces to be arranged. Also, non-rectangular space shapes might be adopted to solve sizing issues of space 47 for instance. In Figure 4b an improved layout has been manually drawn, which is based upon the detailed layout developed by WARGEAR. Table 4c shows the difference between Figure 4a and Figure 4b. Three spaces still don't meet their area requirement, although only by $0.2m^2$, while space 46 still needs significant attention.

3.1.3 Results

During the test case, the results found by WARGEAR were presented and explained to several naval architects. In the following paragraphs, the reactions to WARGEAR's detailed layout plans are described.

One of the first comments given was on the validation of the detailed layouts, i.e. are the answers given by WARGEAR correct, can we trust the results? This is a valid point, and indeed the main objective of the test case. Detailed layouts can be validated by comparison with GAPs. Unfortunately, there was no GAP available for every variation studied. Therefore not all results could be validated. However, when a GAP was available, the results of WARGEAR were very comparable, see Section 3.1.1.

Further comments were mostly related to the visualisation of detailed layouts to naval architects. Improvements on this area help obtain more design insights and thus help support the stakeholder dialogue, Section 1:

- In previous versions of the code, the visualisation of the detailed layout only contained the arranged spaces and a grey deck shape, as shown in Figure 5a. Later, certain Functional Building Blocks (FBB) which could not be used for space arrangement, e.g. exhaust casings, were shown as black areas. FBBs are the main elements of functional arrangements, refer to Takken (2009); Andrews and Dicks (1997). However, this still

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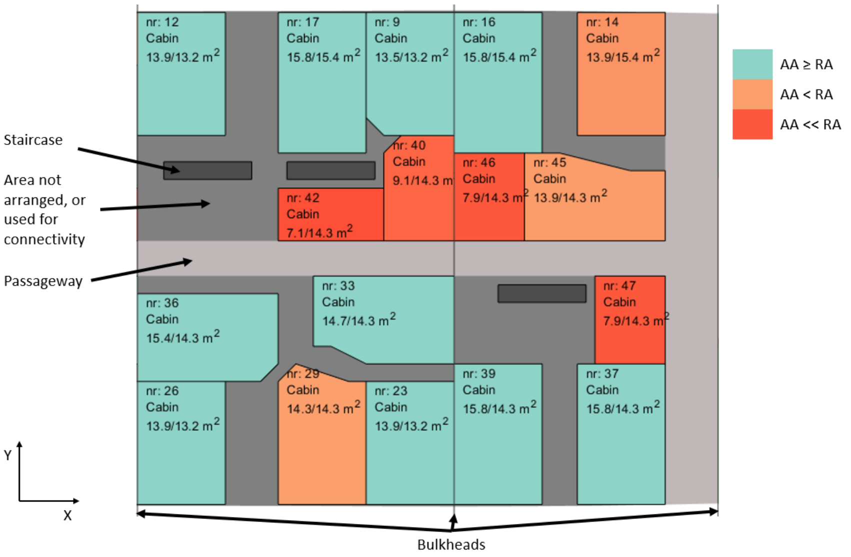
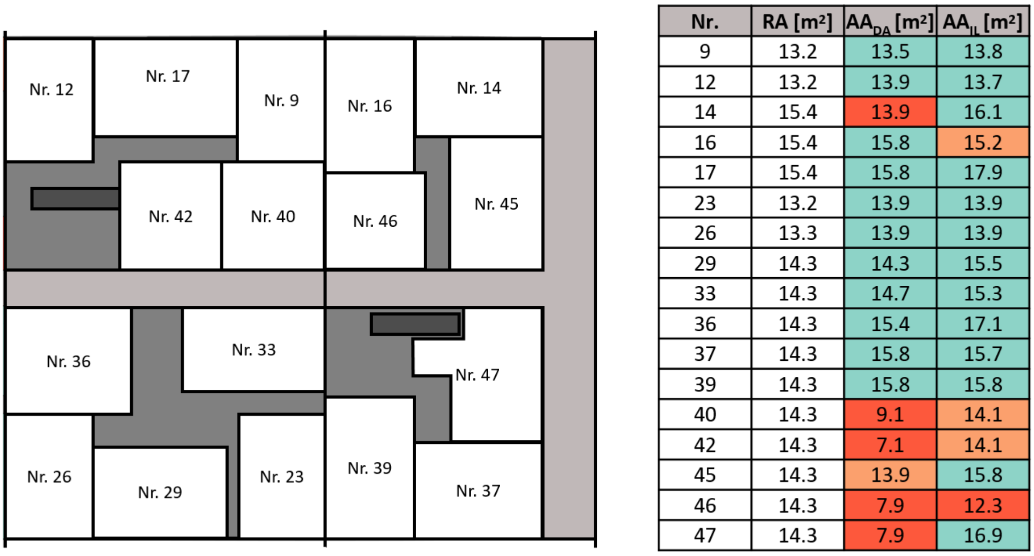
[2] Spaces in WARGEAR are allowed to overshoot their required area by 20%, or any value set by the user, to meet their allowed aspect ratio



(a) The detailed layout as generated by WARGEAR, scoring $A_j = 27.1$



Nr.	RA [m²]	AA_{DA} [m²]	AA_{IL} [m²]
9	13.2	13.5	13.8
12	13.2	13.9	13.7
14	15.4	13.9	16.1
16	15.4	15.8	15.2
17	15.4	15.8	17.9
23	13.2	13.9	13.9
26	13.3	13.9	13.9
29	14.3	14.3	15.5
33	14.3	14.7	15.3
36	14.3	15.4	17.1
37	14.3	15.8	15.7
39	14.3	15.8	15.8
40	14.3	9.1	14.1
42	14.3	7.1	14.1
45	14.3	13.9	15.8
46	14.3	7.9	12.3
47	14.3	7.9	16.9

(b) A manually improved layout, scoring $A_j = 2.5$

(c) Comparison between required area (RA) and achieved area (AAR) in both the detailed and the improved layout (IL)

Figure 4: Example layout of two compartments on one deck as generated by WARGEAR and an improved layout generated by the authors

gave limited insight in the total layout of the vessel. Therefore it was decided to improve the visualisation by including all FBBs which were not further arranged by WARGEAR. To support the comprehension of the detailed layout, the colours from the functional arrangement were used.

- In the past, area success has been defined as missing grid cells in regards to achieved and required area (Le Poole et al., 2019). However, this gives limited insight into the actual square meters missing, since the score has to be multiplied by the squared grid size (typically $0.6^2 = 0.36\frac{m^2}{\text{gridcell}}$), which is inconvenient. To better inform the naval architect, WARGEAR now calculates the actual missing square meters.

- The use of green and red colour shades gives direct insight which spaces have or haven't met their required area (Le Poole et al., 2019). However, it proved difficult to communicate the extent to which spaces did not meet their required area via various shades of red, because the shades provided to less information on the actual achieved and required area of spaces. Therefore it was proposed to present the actual achieved area and required area for each space in the detailed layout as well. After discussing one of the layouts with a naval architect the space name was also added to enhance insight.

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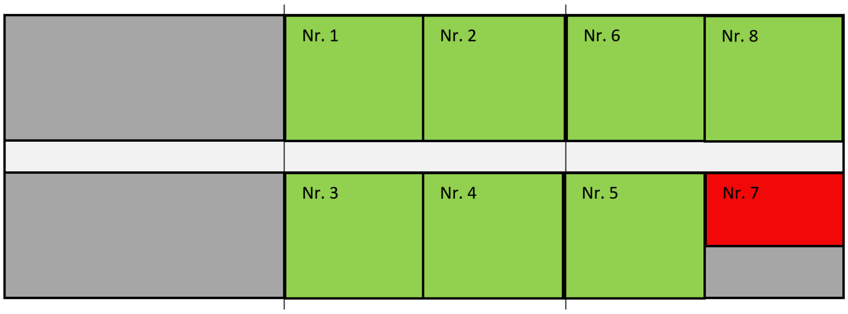
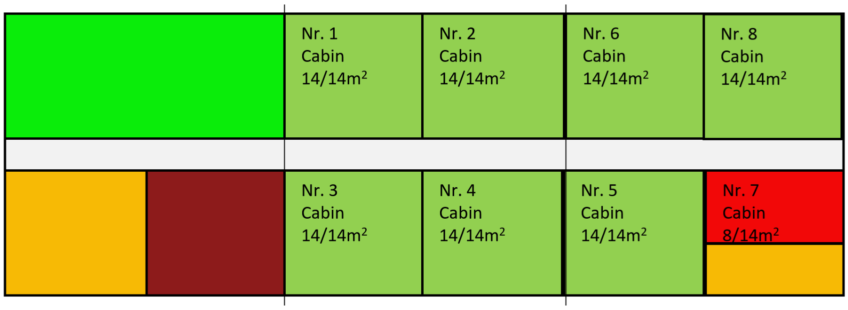


(a) Layout visualisation as in Le Poole et al. (2019).



(b) Updated layout visualisation.

Figure 5: Comparison between layout visualisation in Le Poole et al. (2019) and the updated visualisation presented in this paper. The example comprises three compartments, eight spaces, and four fixed FBBs.

To provide a visual comparison between the past and current visualisation of detailed layouts, see Figure 5. These figures show three compartments of which only two compartments contain spaces arranged by WARGEAR. In the third compartment one FBB cannot be used for space arrangement. While this is immediately clear from Figure 5b, Figure 5a will likely make naval architects wonder why space 7 cannot be fully arranged, due to the missing context.

Therefore, these changes to the visualisation of the detailed layout allow naval architects to get more direct insight in the success of the layout. Based on an investigation of the detailed layout by naval architects, additional variations to the space list or adaptions to the functional arrangement can be made. Naval architects can also accept the detailed layout as a starting point for further detailing into a GAP, even if the detailed layout has not met the required area of all spaces. If, for example one space has achieved 14.5 of the required $15m^2$ and some free area is available, naval architects are likely able to solve this by rearranging spaces, or by using more elaborate shapes to arrange spaces, such as L-shaped spaces. As noted earlier, WARGEAR gives a good initial starting point including an analysis of where potential area problems arise.

3.1.4 Lessons learned

This section will elaborate on lessons learned from the first application of WARGEAR at the DMO. The lessons learned can be divided into two categories, (1) tool related and (2) process related. They area elaborated below:

1. *Tool related*
   Some issues were identified related to the input of the functional arrangement into WARGEAR.
   - The designation of decks is used to identify the damage control deck (DCD), amongst others. To identify the DCD, WARGEAR tries to find the deck called ‘DCD’, naming which had been used in previous designs. However, in this test case WARGEAR was not able to find the DCD, because the deck was designated ‘DCD-deck’. This issue can be solved by a mandatory check of deck names at the input phase of the tool, or by a user input.
   - The curvature of the ship’s keel caused errors during the generation of the positioning matrices (see Le Poole et al. (2019)). Since WARGEAR can only arrange flat decks, only decks which are not affected by the curvature of the keel line can be loaded into the tool. However, in most cases this is no problem as mainly tanks and engine rooms are allocated below the waterline, which fall outside the scope for the project. In order to allow the arrangement of curved parts of the hull, these parts could be vertically projected to a flat deck, as shown in Figure 6.

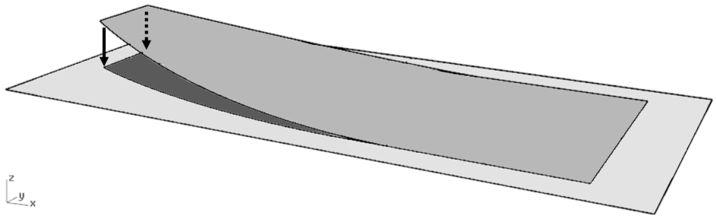
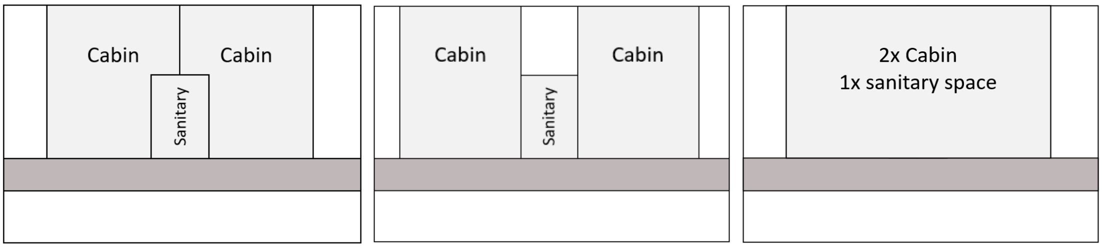


Figure 6: Projecting a curved deck to a flat deck plane.

- Currently the floor plan of each deck is used for the arrangement of spaces. However, the ceiling area of a deck might be smaller than its floor area, which is often the case in naval ship's superstructures for instance. Therefore both the floor and ceiling plans of each deck need to be considered when creating the positioning matrix for spaces.

2. *Process related*
   In preparation of the test case, a generalised input file was developed to improve usability. The test case also revealed the following issues:

   - A reporting method for traceability is currently missing. Therefore design variations need to be stored in separated input files. However, the results from the calculations and the rationale behind the variations cannot be stored in an integrated data set at the moment. Such integrated data set is essential for traceability and documentation of results, as lessons learned will be easily lost otherwise.
   - The test case also showed that very small spaces, such as single sanitary units of approximately $2m^2$, are difficult to arrange correctly. This is particularly the case when an efficient arrangement requires large and small spaces to be alternately placed. If naval architects already envision a particular solution, e.g. as shown in Figure 7a, they might congregate a larger and smaller space to guide WARGEAR and thus to improve the quality of the overall layout, as shown in Figure 7b and Figure 7c. The disadvantage of this approach is that these larger congregated spaces can be harder to arrange.



(a) Envisioned arrangement of two cabins and one sanitary space

(b) Theoretical best solution for WARGEAR

(c) One functional block to be arranged by WARGEAR, representing Figure 7a

Figure 7: Congregation of multiple spaces to improve detailed layout quality

3.2 Test case 2: WARGEAR introduction

Following the execution of the first test case, the authors presented the WARGEAR tool to eight naval architects and senior officers and managers at the DMO. The aim of this presentation was to strengthen the acceptance of the tool into the DMO ship design process by providing insight into the tool and its capabilities. The main topics were a recapitulation of the project proposal, the requirements developed for the tool, the principle mathematical working mechanisms, and the envisioned use of WARGEAR in the DMO design process. The latter was illustrated and supported by the results of the validation test case, described in Section 3.1. The feedback was not recorded during the presentation itself but documented immediately after the presentation, and subsequently further processed. In total twenty comments were recorded. Processing these comments, three categories could be distinguished, namely: Usability, Reliability, and Application. In the remainder of this section the main comments for each category will be discussed.

In general the naval architects were positive about the possibilities WARGEAR provides to rapidly generate detailed layout plans. The presentation was seen as informative, both on the side of the mathematical background of the tool, as well as on the presentation of the results and possible applications of WARGEAR.

Usability

The usability category concerns how willing naval architects are to use the tool in their work and what additions to the tool will be required to improve usability. The comments provided in this category mainly concerned the generation of the required input for WARGEAR. Other comments relate to the ability of naval architects to positively influence the quality of the detailed layouts.

Input generation

Several comments addressed the generation of the space list. During the presentation, some concerns were already taken away by explaining that only 30 minutes were required to generate the first variation of the space list for test case 1. Later variations took even less effort. However, more efficient generation of the space list is possible, e.g. via a default sheet or by making use of recent research carried out at the DMO to generate the space list based on requirements (Van der Weg, 2020).

At the moment only FBBs can be used to specify the preferred location of spaces, which is sufficient in general. However, naval architects might want to allocate spaces into a specific compartment. Because FBBs can overlap with multiple compartments, see Figure 8, a compartment specific allocation is currently not possible. To efficiently translate the naval architect's mental picture of the allocation of spaces to compartments to WARGEAR input, existing tools at the DMO, such as FIDES, and WARGEAR need to be coupled. It has been determined that the DMO will ensure the proper coupling between tools. Efficient generation of the space list is considered to be sufficient for the WARGEAR project, while tool integration is considered out of scope.

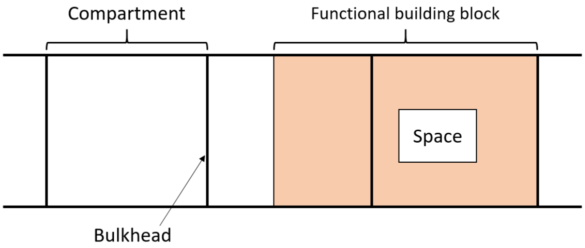


Figure 8: Visual explanation of the subdivision of a deck, presented in a top-down view. A FBB overlapping multiple compartments is shown (Le Poole et al., 2019)

Quality of layouts

The naval architects would like to have increased control over the dimensions of spaces. Currently space sizes (length and width) are determined by required area and a range of allowed aspect ratios. However, some discrete sizes might not be preferred because efficient arrangement of furniture can be challenging or impossible. In the current setup of the tool, the implementation of this feature is relatively easy. However, the workload in the Input phase of the WARGEAR process needs to be carefully considered, i.e. naval architects should not be overloaded with checks upfront as this would be considered a hindrance to use the tool. The amount of required input and the quality of the layouts needs to be balanced properly.

To properly test the usability of the WARGEAR tool, future test cases should also be performed by DMO naval architects. Only by hands-on experience and use of the tool, the bottlenecks in the work flow will emerge. Subsequently, improvements to the usability of the tool can be implemented. An example could be a list of standard cabin sizes, to reduce the effort required for WARGEAR input generation.

Reliability

The reliability category covers comments concerning the tool's ability to generate accurate detailed layouts. One of the naval architects addressed the implementation of staircases in WARGEAR, as the sizing of a staircase at the lowest and upper deck is equal to the sizing of the staircase on intermediate decks. In reality, the area around the staircase on the lowest and upper deck can be used more efficiently, as indicated in Figure 9. By simplifying staircases, WARGEAR provides a slightly conservative estimation of the total area required for staircases.

During the presentation, the aim of WARGEAR was discussed. WARGEAR has not been developed to replace naval architects, but to support them in their work by providing quick insight into layout sizing and integration problems. However, the work of the naval architects is certainly taken as a benchmark for the quality of the detailed layouts during validation of WARGEAR. Indeed, to be used extensively at the DMO, WARGEAR should perform at least at a comparable level as naval architects as the results should be reliable and give sufficient insight in layout risks. The results of test case 1 was sufficient proof to the audience that WARGEAR is sufficiently able to

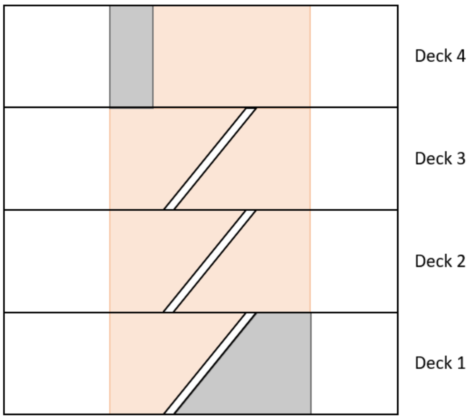


Figure 9: Difference between open area required around ship staircases in reality (orange) and area arranged by WARGEAR (orange and grey).

answer the questions of interest. However, some new test cases were proposed to ensure that WARGEAR is able to arrange naval surface ship types relevant for the Netherlands Navy. These test cases will be carried out with and by DMO naval architects, as described above.

It was also stressed that the WARGEAR tool should be able to generate detailed layouts that comply to *rules*, and that therefore not all *exceptions* should be modelled. It is believed that modelling exceptions will decrease the effectiveness of the code, as it will increase the number of requirements to which detailed layouts should comply. Also, the number of exceptions will increase with every new ship type. One attendant put this as: ‘Experience tells us that there will always be something that we had not thought of’. Therefore WARGEAR needs to use the set of rules that will result in reliable layouts for as many ship types as possible. Exceptions are then dealt with when manually translating the WARGEAR results into a GAP.

Application

The application category relates to the usability category, and covers the comments on the integration of WARGEAR in the DMO design process and the types of design problems WARGEAR can be used for.

In FIDES, FBBs are sized based on the required area of spaces and an area margin for additional logistic systems, such as staircases. The attendants would like to see a feedback loop between WARGEAR and FIDES to improve the initial area estimations and margins. This could be done by relating the area required for spaces and logistic systems in the detailed layouts to the initial estimated area and margins in the functional arrangement. However, before altering the FIDES input, a manual generated GAP needs to be generated for a detailed assessment of all aspects of a layout. Nonetheless, the difference in required and anticipated areas will be communicated to the naval architects so they can use this information to improve sizing of the functional arrangement, which is one of the objectives of WARGEAR in the first place.

All attendants agreed that the detailed layouts provide significant insight in layout sizing issues. Notably, the detailed layouts prompted the naval architects into spontaneous discussions about design variations, such as the benefits of single versus double passageways. Although the presentation was not aimed to prompt these discussions, it indicates that the detailed layouts can be used for other purposes than just validation of functional arrangements. One of these roles is to provide a starting point for the generation of GAPs, which could support the stakeholder dialogue later in conceptual design, Section 1.

Another possible use that was identified, is the validation of designs with an even lower level of detail than functional arrangements. For example, at the DMO another ship design tool, the Packing approach, (Van Oers et al., 2018; Van Oers, 2011), is used to generate low detail designs with the aim to explore initial requirements. A rough translation of a ‘Packing’ design to a functional arrangement might allow the generation of detailed layouts in limited time, and thus enable more in-depth validation of initial requirements. This would be beneficial to improve initial budget estimations, for example. However, the translation of a ‘Packing’ design to a functional arrangement might be challenging because the internal layout of the former lacks a significant level of realism, which could be time-consuming to solve.

A question was raised whether WARGEAR can be used to arrange machinery spaces. This falls outside the scope for the project, but would be an interesting study. WARGEAR cannot readily arrange machinery, since the arrangement of machinery differs from the arrangement of spaces at various points. For instance, space size is more flexible than machinery size, positioning of machinery is more restricted by ship stability constraints, and access to machinery needs to be taken into account as well as pipe routing and length (Van der Bles, 2019).

4 Conclusions and future research

During early stage naval ship design the focus is on developing a set of technical and financial feasible requirements. To validate the technical feasibility of requirements, concept designs are developed. For these concept designs, the development of detailed General Arrangement Plans (GAPs) is essential, as GAPs are used in the stakeholder dialogue (to find out what is actually wanted) and to validate lower level of detail concept designs (to find out what is actually technically feasible). The manual generation of these GAPs is time consuming. To support the development of these GAPs, the WARGEAR project aims to develop a tool that is able to quickly generate sufficiently detailed layouts plans to support naval architects in the validation of lower level of detail concept designs.

This paper has presented the results of the first test case conducted with the WARGEAR tool. This test case had a twofold goal, namely (1) tool validation, and (2) user acceptance.

1. **Tool validation**
   A comparative test case showed that WARGEAR is able to generate detailed layouts plans that compare well to GAPs previously generated by naval architects. However, naval architects require days to provide the same insight, which could be provided by WARGEAR in a matter of hours. This will enable naval architects to spend their time on solving sizing and integration issues, rather than identifying these issues.
   The test case revealed the tool has some limitations in arranging very small spaces, although this is not seen as a concern at the moment.

2. **User acceptance**
   To strengthen user acceptance, the results of the test case were shared with multiple naval architects and senior officers and managers at DMO. The attendees were generally positive but also provided several comments and questions regarding the test case and the WARGEAR tool. These comments were documented and processed following the meeting. Three categories were identified, namely usability, reliability, and application related comments, which will be addressed in the remainder of the project.

Future research will focus on: (1) further tool and methodology development, and (2) testing on various warship types.

1. **Tool and methodology development**
   (a) As stated in Le Poole et al. (2019), the focus is on developing WARGEAR such that feasible layouts can be generated for different ship design cases, e.g. fleet auxiliary vessels, surface combatants, and Landing Platform Docks.
   (b) Managing data for different design cases and scenarios has not been a priority in the project. The test case revealed that this topic needs to be addressed to enable efficient application of the WARGEAR tool in the DMO design process.
   (c) Further investigation of the insight gained by applying WARGEAR in ship design cases needs to be conducted. The observations made during this investigation will be used to improve the information flow between naval architects and WARGEAR.
   (d) As indicated in Le Poole et al. (2019), the use of design rationale, such as captured by DeNucci (2012), to improve the quality of layouts is promising. Since the detailed layouts generated by WARGEAR prompted the naval architects into spontaneous discussions on layout aspects, further research will focus on applying WARGEAR in the stakeholder dialogue. The goal is to further develop the WARGEAR methodology such that design rationale can be captured and re-used. This will further improve the efficiency of the early stage design process, and ideally lead to better warship concept designs and requirements.

2. **Testing**
   Following the future tool developments, further testing of WARGEAR will be conducted. The goal of these tests is to build further confidence in WARGEAR as well as to test the tool's limitations. These tests will be conducted using different ship design cases, and will also be conducted by naval architects to address WARGEAR's usability.

In conclusion, the WARGEAR project has made significant steps in reducing the effort required for detailed layout generation. The above mentioned steps will further improve the validity of the WARGEAR tool, and will provide a new tool to accelerate the early stage warship design process. Indeed, as one of the attendees in the user acceptance presentation said: 'If WARGEAR proves to handle all relevant types of ships, WARGEAR will certainly, and as soon as possible be implemented in the DMO ship design process'.

5 Acknowledgements

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6 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 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.

Due to confidentiality, source code of the tools and data used in this paper are 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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