Integrating detailed layout generation with logistic performance assessment to improve layout insights in early stage warship design

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Synopsis

The performance of ‘internal layout and process driven ships’ is dominated by its operational processes. These operational processes are of a logistical nature. Therefore these processes have a significant impact on the arrangement of these ships. Early stage design efforts are aimed to understand the interaction between the layout and the operational processes aboard these ships to gain timely design insights to inform the decision-making process.

Therefore, sufficiently detailed concept designs are to be generated by naval architects and analysed to de-risk requirements. While various tools have been developed to support naval architects in generating layouts with an increasing level of detail, the detailed evaluation of operational performance is typically postponed to the stage that only little change to the design is possible. Hence, the naval architect’s expertise is currently crucial to develop concept designs with acceptable operational performance. However, this limits the amount of explicit insight in layout performance available to decision makers. Therefore there is a need for an operational evaluation method that supports layout development in early stage ship design.

To address this mismatch between layout generation and evaluation, this paper proposes an integrated method that allows naval architects to concurrently generate and evaluate sufficiently detailed layouts. A test case is presented in which the proposed method is used to generate a detailed layout for a Landing Platform Dock (LPD) and evaluate this layout based on operational processes.

The test case shows that the method can indeed be used to generate and evaluate detailed layouts of internal layout and process driven ships. However, the implementation of tooling for this method proved to be challenging and thus requires further attention. Nonetheless, the test case indicates that the proposed method will improve early stage ship design by helping naval architects to better understand the complex interrelation between layout and operational processes.

Keywords: early stage ship design; layout generation; layout evaluation; operational processes; queueing; WARGEAR

1 Introduction

Various types of ship design problems can be classified based on ‘design drivers’, i.e. the characteristics of the design that have the largest influence on the eventual vessel’s performance. One of these types of ship design problems concerns ‘internal layout and process driven ships’ (Droste et al., 2019). The performance of this type of ships is dominated by its operational processes. These operational processes are of a logistical nature and therefore have a strong influence on the arrangement and sizing. For instance, the aircraft landing and take off process has a significant impact on the arrangement of the flight deck and hangar of an aircraft carrier (Knight, 2009). Another example is the arrangement of a cruise ship, which is dominated by the envisioned passenger experience and expected movement of passengers around the ship. Because of the strong relation between the layout and the operational processes it is necessary to study and understand this interaction early on in the design process, to gain timely insights to inform the decision-making process.

Indeed, the early ship design stages are characterised by a large design freedom, easily changing requirements, limited understanding of the design problem, and, at the same time, the most important design decisions are made here (Andrews, 2012). Because of the wicked nature of ship design, an iterative design process is used to increase design knowledge by developing alternative concept designs with sufficient detail to de-risk requirements (Van Oers et al., 2017).

Hence, both layout generation and evaluation of operational performance of internal layout and process driven ships should take place in early stage design. Various tools have been developed specifically for layout generation in early stage design, e.g. Packing (Van Oers, 2011), FIDES (Takken, 2012), DBB (Andrews and Pawling, 2003), ISA (Parsons et al., 2008), and WARGEAR (Le Poole et al., 2019, 2020). These tools are all used in early stage

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Author’s biographies

Ir. Koen Droste is currently pursuing a PhD at Delft University of Technology at the department of Maritime & Transport Technology, focused on ship general arrangements exploration during early ship design stages. He obtained his Bachelor degree in maritime technology between 2011-2014 and subsequently completed a Master study in 2016 which specialised in ship design. As a part of the MSc-program, an exchange program was participated with Aalto University in Finland during which courses specialising in Passenger ship design and Ice operations were studied. The final MSc project involved a concept exploration study for a small passenger vessel designed for Arctic operations.

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.

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design, but have been developed for slightly different goals, e.g. concept exploration via low level of detail designs (Packing) or concept validation via higher level of detail layout plans (WARGEAR).

However, detailed analysis of operational performance is often postponed to the moment only little change to the design is possible, because a significant level of detail is necessary for evaluation, yet often not readily available. Therefore the naval architect's expertise is crucial for developing concept designs that are acceptable from an operational performance perspective, when no tools are available to evaluate this performance. To address this issue various research developed methods to evaluate operational performance, for instance based on networks (Roth, 2017; Gillespie, 2012; Rigterink et al., 2014; Le Poole, 2018) , or based on multi-agent modelling (Li et al., 2019; Andrews and Pawling, 2008). However, these methods use either low level of detail layouts or very high level of detail layouts respectively. The former are not sufficient for de-risking requirements, while the latter are only available during the contract engineering phase of the design process.

Efficient generation of operationally satisfactory layouts requires a method that enables a coherent, balanced, and timely layout evaluation during layout generation. However, the integration of both layout generation and evaluation is an even more challenging, yet necessary, research task.

The addition to the early stage design process of a method that matches the level of detail of the generation and evaluation of layouts, increases the design insight available to naval architects and decision makers. However, because of the complexity of the detailed layout generation and evaluation tasks, a significant level of automation will be required to support the generation and evaluation of multiple alternatives in a cost-effective way. Multiple advantages can be distinguished that support such expansion of ship design capabilities during early design stages:

1. Increasing the level of detail of ship layouts enables the identification of potential sizing and integration issues, as well as improving the accuracy of logistic performance analysis, as more complex interactions in the layout can be studied. However too much detail may draw the attention to details before major design issues have been studied. Therefore the level of detail has to be carefully balanced with the advancement of the design project as a whole.

2. Gaining such insights earlier in the process enables the adaption of concept designs while less aspects have yet been fixed, and thus changes to the design have less implications on the overall project resulting in less rework costs, more design freedom, and more robust designs (Duchateau, 2016).

3. Since the naval ship design process is complex due to endogenous, exogenous, and temporal factors (Shields et al., 2017), naval architects and decision makers need to be able to objectively distinguish between design alternatives. Using tools to evaluate the operational performance of concept designs, an objective comparison between this performance for multiple alternatives is enabled.

4. The ability to generate and evaluate higher level of detail designs allows the exploration of more detailed questions or trade-offs with a considerable effect on the performance in a set-based manner (Singer et al., 2009). Examples are whether to use single or double passageway configurations, how to arrange staircases, or to analyse mess capacity and regime.

In an attempt to address this challenging problem, this paper proposes a method that relates layout generation and evaluation, suitable for early stage ship design. The remainder of this paper will elaborate on the proposed method in Section 2, as well as the tools used to generate and evaluate the detailed layouts. In Section 3 a test case will be introduced which will be used to demonstrate the benefits of the integrated method. Subsequently, in Section 4 the results of the test case will be presented and analysed. The paper will conclude with a discussion and conclusion on the proposed method, and identify key issues to be taken into account in future research.

2 Method

2.1 Method overview

For the purpose of studying internal layout and process driven ships during early design stages a method has been developed as shown in Figure 1. This method consists of ten steps with activities varying from data collection, space arrangement, modelling and simulation, and evaluation.

1. *Collect processes and activity information* The first two steps collect the input for the method. Step one focuses on collecting information regarding the operational processes and corresponding activities aboard the to-be-designed ship. This information exists of attributes of the processes, activities in those processes and number of people involved.

2. *Collect system and space information* Step two collects the other half of the input, the space and system information. This includes information regarding size, name, capacity, or required location. These first two steps are the starting point of the process, however as will be explained in step 9 the inputs collected here may be changed based on new insights gained from the method.

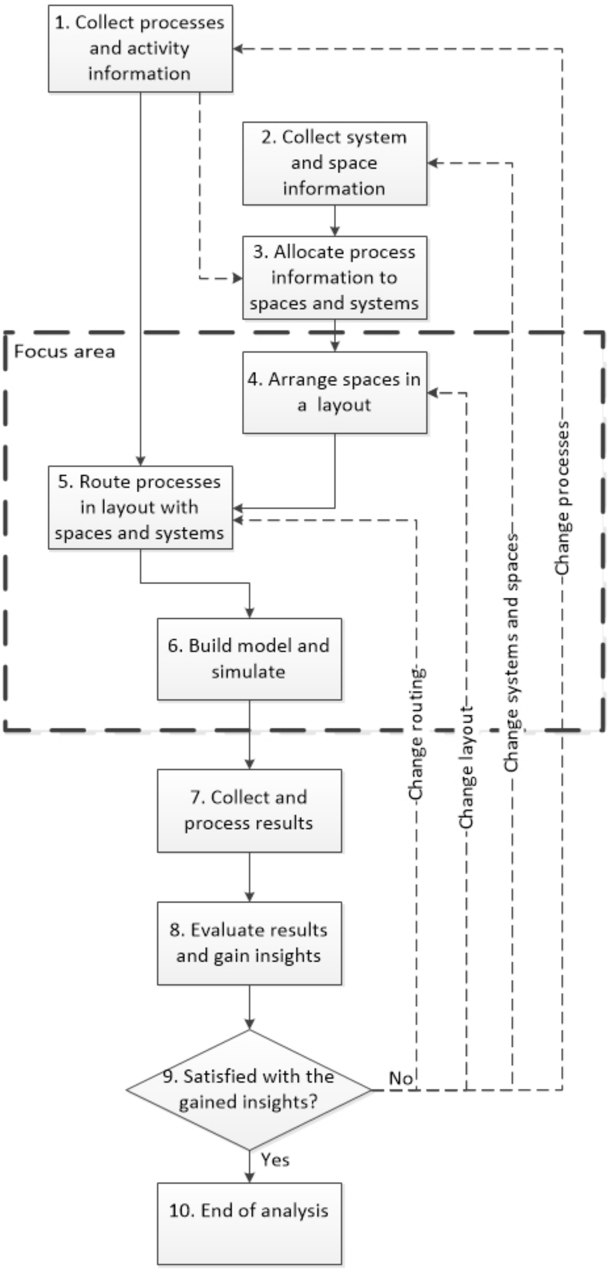


Figure 1: Flowchart

3. *Allocate process information to spaces and systems* Step 3 allocates the activities collected in step 1 to the spaces and systems collected in step 2. This allocation allows an arrangement method (such as in Le Poole et al. (2019)) in step 4 to use these process relations between spaces to adapt the arrangement.

4. *Arrange spaces in a layout* Step 4 arranges the spaces collected in step 2 into a technically feasible layout. Multiple methods to generate layouts exist, as shown in Section 1. In this paper the WARGEAR method (Le Poole et al., 2019) is used, because 1) it is able to generate high level of detail layouts with limited input from naval architects in near-real time, and is therefore suitable for the problem outlined in Section 1, and 2) it is being developed by this paper's second author.

   WARGEAR is developed to generate detailed 2D layout plans, such as shown in Figure 2, based on a predefined 3D functional arrangement. In Figure 3 an example of a functional arrangement is shown, which has been generated in the design tool FIDES (Takken, 2012). The purpose of these detailed 2D layout plans is to de-risk spatial requirements that cannot be evaluated in the 3D lower level of detail functional concept design. The functional arrangement sets design parameters like hull and superstructure shape, bulkhead

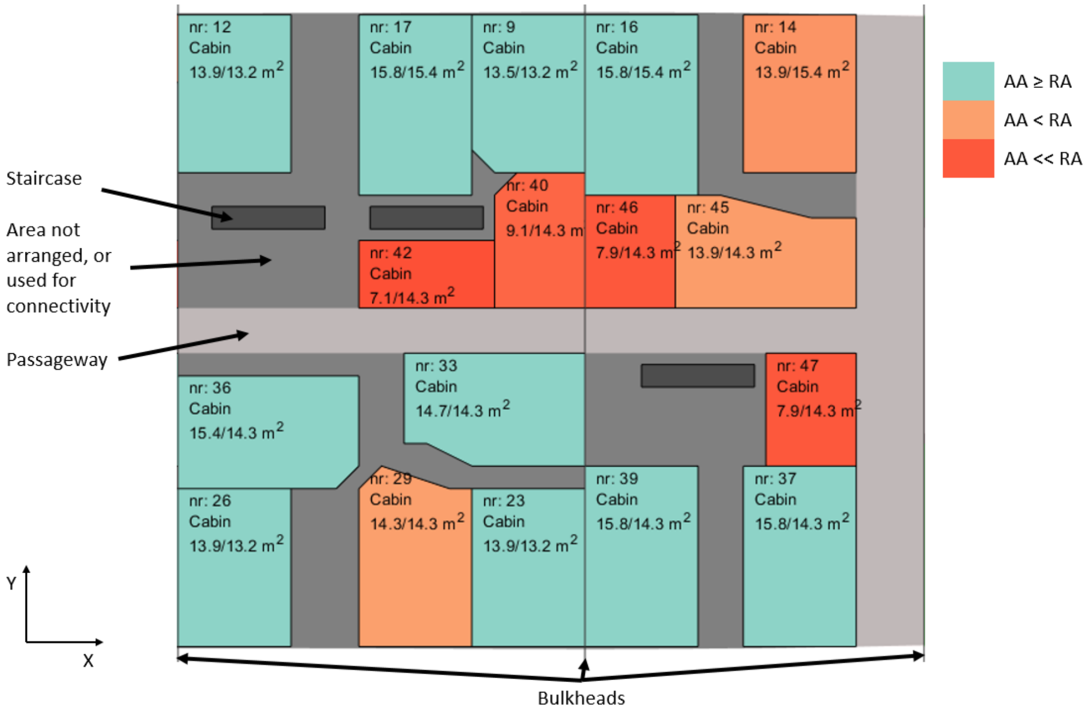


Figure 2: A detailed layout of two compartment as generated by WARGEAR (Le Poole et al., 2020)

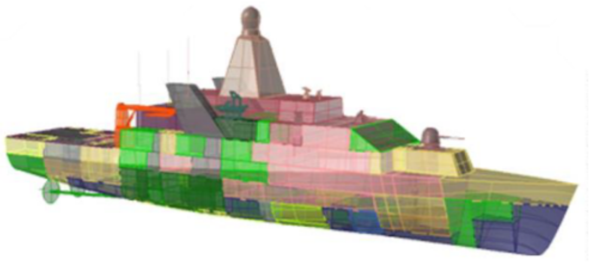


Figure 3: An example of a functional arrangement as generated in FIDES (Van Oers et al., 2017)

positions, and casing positions. Besides a functional arrangement plan, WARGEAR requires a complete list of spaces as input. The tool attempts to arrange spaces such that they meet their required area and aspect ratio, and can be accessed from the main passageways. The tool is best suited to arrange ‘soft spaces’, i.e. spaces which dimensions are not necessarily fixed, such as cabins. The naval architect therefore might use WARGEAR to arrange an accommodation compartment of the ship to assess whether sizing and integration issues might occur in that compartment (Le Poole et al., 2020). The perceived level of detail of the layout plans is to the level of spaces without furniture (Le Poole et al., 2019).

To assess each detailed layout, the achieved area (AA) of each space is compared with its required area (RA). A total score for each generated layout j is given by Equation 1. In this equation, spaces are not allowed to compensate for spaces that don’t meet their RA. For example, if two spaces with $RA = 10$ are arranged with $AA_1 = 5$ and $AA_2 = 15$, then the space 2 does not compensate the insufficient area of space 2. The score for this design would be $A_j = 5$, instead of $A_j = 0$ when area is compensated. Equation 1 is also used as objective function in WARGEAR, and is minimised (Le Poole et al., 2019).

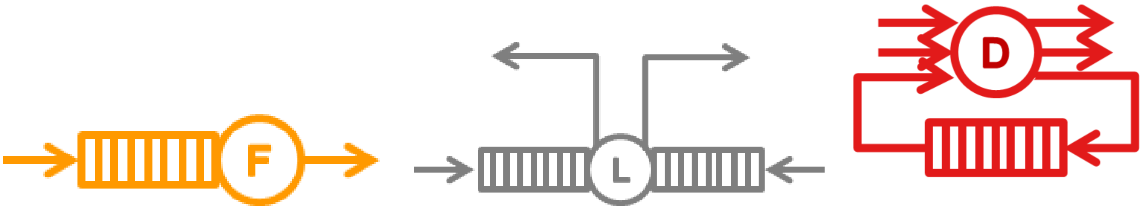
$$A_j = \sum_{i=1}^{n_{space,j}} \max(0, RA_i - AA_i) \tag{1}$$

Additionally, the detailed layouts generated by WARGEAR are presented to naval architects for further visual investigation. For background on the tool’s mechanics, as well as an elaboration on the use of the

WARGEAR method, please refer to Le Poole et al. (2019, 2020).

5. *Route processes in layout with spaces and systems* The activities in a process can be divided in two categories, functional activities and logistical activities (Le Poole, 2018). The functional activities are allocated in step 3, but the actual routing and thus allocating of the logistical activities to particular passageways and staircases can only be done in an actual arrangement. The routing can be done using many techniques for example: manually created paths, or paths generated by shortest-path algorithms, such as Dijkstra's algorithm (Dijkstra, 1959) or Yen's k-shortest path algorithm (Yen, 1971). These are all forms of statically defined paths, i.e. they do not change during the simulation of the model. Alternatively a dynamic path finding algorithm can be implemented in the evaluation model and to determine the paths based on crowd densities or accessibility during the simulation. One example of such a method is a Markov based path finding method (Kana and Droste, 2019).

6. *Build model and simulate* The sixth step is the modelling and evaluation step. This paper uses a queueing based method developed by the first author to evaluate the onboard processes and their impact on the designed logistics. This method uses finite capacity queueing networks to evaluate ship layouts. The simulation models in this method are built using three sub-systems: a functional sub-system, a logistical sub-system, and a decision sub-system as visualised in Figure 4. Any functional space such as cabins, a mess, or a command centre are modelled using a functional sub-system, Figure 4a.Furthermore any space with the main function of logistics, such as passageways, staircases, or elevators are modelled using a logistical sub-system, Figure 4b. The third sub-system is the decision sub-system, Figure 4c. This sub-system is used to implement the routing logic into the model. Therefore these nodes are located between any of the other nodes. In the layout this would be at any door, intersection, or other location where a decision regarding the route needs to be made. Together these building blocks form the modelling architecture used for the queueing model. This architecture is first presented in Droste et al. (2019) and has since then be modified with a priorities and a pre-emption system to reduce deadlock. Deadlock is a situation where no further events can happen because entities are blocking each other in moving forward in their processes. However, these method improvements will be discussed in a future publication.



(a) Functional sub-system (b) Logistical sub-system (c) Decision sub-system

Figure 4: Multiple diagrams depicting the various sub-systems of the model architecture.

7. *Collect and process results* Step 7 deals with the collection and processing of the results. This includes activities as creating animations and graphs, or calculating additional metrics.

8. *Evaluate results and gain insights* Eventually in step 8 the evaluation of results happens. Opposite to most of the previous steps, this is an activity done by the naval architect and very little automation is pursued here. Where in the other steps automation is key to reduce the required effort and chance on human errors, here the creativity and skills of the naval architect are required for a good analysis.

9. *Satisfied with the gained insights?* Step 9 is a decision point where lessons learned are reflected and various alterations can be done to expand the explored design space until sufficient insight is gained. Within this method four types of changes are proposed:

   Change 1 The processes as collected in step 1 can be changed when analysis learns that operating in a different manor provides more affordable results.

   Change 2 The definition of systems and spaces can be changed to include different systems, other system capacities, or multipurpose systems.

   Change 3 The layout can be changed to study the effect of relative locations of systems on passageway utilisation and overall performance.

   Change 4 The routing can be changed, for some design purposes evaluating variants of fixed routing representing expected usage or various circulation plans might present valuable insights.

10. *End of analysis* When sufficient insight is gained within the established limitations of time and money the method ends in step 10. These ten steps are believed to provide a holistic overview of a layout generation and analysis method for internal layout and process driven ships.

2.2 Enabled automation by tool integration

This section will elaborate on the integration of the layout generation and evaluation steps. In step six of the method the layout evaluation model is built and simulated, using the layout and process information resulting from the first four steps of the method. In previous test cases, see Droste et al. (2019), simulation models have been manually created. However, the method presented in this paper presents the following two challenges:

1. The method has an exploratory nature and therefore includes various feedback loops, i.e. the need for more design insights can lead to design variations. Therefore manual model generation would turn out laborious.
2. Contrary to previous test cases, this paper addresses the generation and evaluation of layouts with a substantial level of detail, which require larger simulation models to be created. Manual simulation model generation could lead to modelling errors, which could be time-consuming to find.

However the combination of this method with the available tooling creates the situation where sufficient information is available to address these challenges. This is realised by optimising the exchange of information between the different tooling. Therefore a substantial level of automation needs to be realised, as mentioned in Section 1. This level of automation has been achieved in step 4, 5, and 6 of the method. These achievements are elaborated on next:

1. Step 4. *Arrange spaces in a layout.*
   After each arrangement attempt of WARGEAR, Section 2.1, one or more detailed layouts are selected by naval architects for logistic performance evaluation. Subsequently, each selected layout is semi-automatically translated into a network with the required functional, logistical, and decision sub-systems of the queueing architecture as nodes. The use of networks allows the translation of a layout into a queueing simulation model, as well as the automation of process routing. The current implementation of the method in WARGEAR requires naval architects to check the network representation of each layout for missing connections. However, full automatic generation of the network is believed to be possible, but has not been pursued for the purpose of this paper. After network generation, the network is sent to the queueing tool for layout evaluation.

   In the network representation, the geometric centre of each functional space is taken as the position of a functional sub-system. Likewise passageway segments are represented by horizontal logistical sub-systems at the centre of the passageway segments. Vertical logistical sub-systems represent staircases. The current implementation of the queueing tool does not allow multiple functional sub-systems to be connected to a single decision sub-system. However, in detailed layouts such situations occur often, for instance, at some point in a passageway a person might be able to choose between a door to his/her left and right. Moreover, decision sub-systems can only be connected by logistical sub-systems. To be able to model this level of detail in the queueing tool, additional sets of decision and logistical sub-systems were introduced. This is shown in Figure 5, where a network representation of the layout of a compartment with two passageways and eight spaces is shown. In the figure the additional sub-systems are indicated as square nodes, while the round nodes represent the initial determined nodes. The figure also shows that space 5 and 8 are connected to original decision sub-systems directly, while the other six spaces are connected via an additional set of decision and logistical sub-systems.
2. Step 5. *Route processes in layout with spaces and systems.*
   The network representation of the layout allows the automatic routing of processes through the layout. Dijkstra's algorithm is used in this paper in combination with the network and the process and activity information, as well as the allocation of these activities to spaces, to find the shortest path between two successive activities for each entity. Subsequently these shortest paths for each activity are congregated to create the full paths for each individual entity in the simulation.
3. Step 6. *Build model and simulate.*
   The existing queueing tool is extended with an option to automatically generate simulation models based on the graph generated in step 4. The automatic generation of these models uses the graph exported from the WARGEAR tool, which is conveniently formatted in the model architecture used in the queueing tool. Using this graph the various sub-systems are placed in the model and connected, after which the model is saved and passed on to the evaluation part of the method.

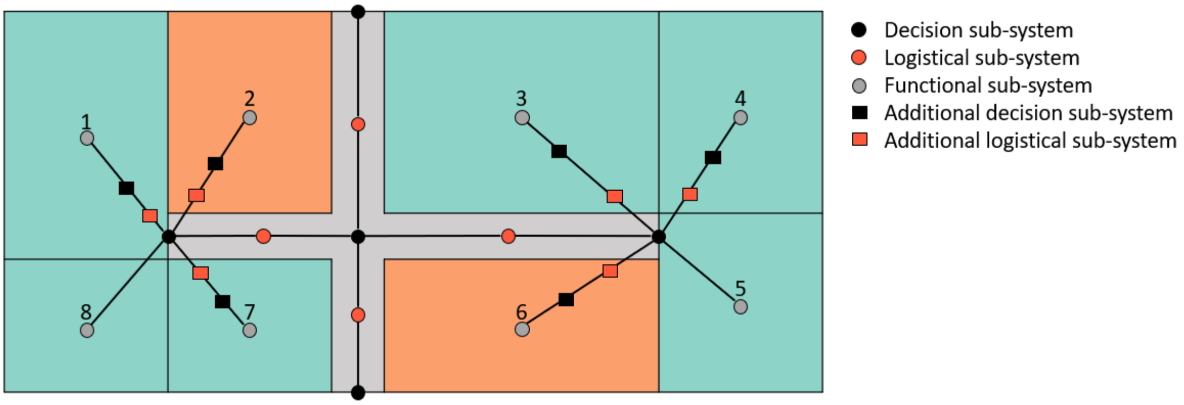


Figure 5: A queueing network representation of a layout with eight spaces and passageways

This level of automation has a number of advantages. Firstly, it reduces the effort require to generate simulation models, and therefore increases the time available to naval architects to use the method to gain design insights with respect to layout and corresponding operational processes. Secondly, it allows for consistent model generation, as well as a reduction of modelling mistakes as less human interaction is required. Thirdly, the ease of use of the overall method is improved and enables a more effective application of the method. Indeed, automating the integration of layout generation and evaluation allows the naval architect to keep its focus on the creative aspects of ship design in the method, (Andrews, 2003), which variations to study and to understand the performance of the layout, and therefore how to design the best layout.

3 Test case setup

To demonstrate how this method supports naval architects during early stage design of internal layout and process driven ships the design of a notional Landing Platform Dock (LPD) is considered as a case study. LPDs are considered to be internal layout and process driven because of the operational processes that involve hundreds of marines, their equipment, weapons, and vehicles. The test case should provide insight into possible bottlenecks in the operational processes as well as the relation of these bottlenecks to the layout of the LPD. This section will elaborate on the the test case setup, which comprises the first three steps of the method.

3.1 Step 1: Collect processes and activity information

Step 1 of the method is to collect 1) all relevant operational processes and 2) corresponding activities. In reality, the definition of these processes and activities will see a dialogue between navy personnel, operational operations specialists, and naval architects. For the demonstration purposes of this paper, a simple operational process has been defined.

1. **Operational process**
   To investigate the logistic performance of the LPD concept design the main operational process of the LPD is the landing of 360 marines to a landing zone at a beach. During the operation the LPD will stay at a significant distance from shore. Two helicopters and two LCVP transport craft will be used as connectors between the LPD and the landing zone.

2. **Activities**
   The operational process is detailed into a number of activities to be completed by the marines. These activities have been allocated globally to system/space type (Table 1). For instance, the activity ‘Cabin’ represents time spend at a cabin. Since the capacity of the connectors is limited, the marines will be transported in a total of eight waves. The first four waves take place in the morning, while the last four waves take place in the afternoon. The first and fifth wave include both helicopter and LCVP movements. The other waves only have helicopters pick up marines from the ship, since the LCVPs have a round trip time of four hours, compared to a round trip time of one hour for the helicopters. The capacity of the connectors is given in Table 2.

   The marines in the first four waves have to complete identical activities, namely: 1) they have to spend time in a Cabin, 2) have breakfast in the Mess, 3) are briefed, 4) return to their cabin to wait for their wave to start, 5) pick up their weapon at the Weapon hand out location, and 6) proceed to their connector. Marines in the afternoon wave spend additional time in their cabin and get lunch prior to the briefing. The daily operations of the LPD's crew have not been taken into account in this study.

Table 1: Operational processes for the LPD test case

			Process activities and corresponding times [minutes]							
		No. of marines	Cabin	Mess	Briefing	Cabin	Weapon hand out	Heli/ LCVP		
Waves	1	28	20	30	60	10	0.5	60 / -		
		68	20	30	60	10	0.5	- / 240		
	2	28	20	30	60	70	0.5	60 / -		
	3	28	20	30	60	130	0.5	60 / -		
	4	28	20	30	60	190	0.5	60 / -		
			Cabin	Mess	Cabin	Mess	Briefing	Cabin	Weapon hand out	Heli / LCVP
	5	28	20	30	180	30	60	10	0.5	60 / -
		68	20	30	180	30	60	10	0.5	- / 240
	6	28	20	30	180	30	60	70	0.5	60 / -
	7	28	20	30	180	30	60	130	0.5	60 / -
	8	28	20	30	180	30	60	190	0.5	60 / -

Table 2: Connector capacity

Connector type	**Number of connectors**	**Capacity**	**Number of transport moves**	**Total marines transported**
Heli	2	14	8	224
LCVP	2	34	2	136
				360

3.2 Step 2: Collect system and space information

Some of the overall requirements for the notional LPD, which include sizing and manning requirements, are listed in Table 3 in Appendix A. Also sizing requirements for logistic systems, i.e. staircases and passageways are provided. In Table 4 in Appendix A additional sizing requirements for individual spaces are listed. The manning requirements combined with the space sizing and capacity requirements define the required number of cabins aboard the LPD.

Based on the two sets of requirements an initial functional arrangement for the notional LPD has been generated, and is shown in Figure 17 in Appendix B. Note that this functional arrangement is still far from complete, e.g. engine rooms, exhaust stacks, fuel tanks, equipment storage rooms, amongst others, have not been implemented, and not all available area has been utilised. However, since the purpose of this paper is to demonstrate an integrated detailed layout generation and evaluation method, this functional arrangement was found to provide sufficient information.

3.3 Step 3: Allocate process information to spaces and systems

Because the capacity and number of spaces (Section 3.2) as well as the arrangement of these spaces can change, the global allocation of process and activities to space types (Section 3.1) needs to be translated to an allocation to specific spaces. The allocation of process activities to specific spaces involves the following considerations:

- The capacity and space type of each space. For instance, a 'MAR-8' cabin accommodates eight marines and can therefore only be in the path of eight specific marines. If a marine is allocated to a specific cabin, this cabin should be used in repeated appearances of 'Cabin' in the activity path for this marine.

- The location of each space. The allocation of activities to marines and spaces can be done such that marines with similar activities accommodate in the same compartment of the ship or such that the logistical load on the ships passageway and staircase network is minimised. Like in Section 3.1, a dialogue between navy personnel, operational operations specialists, and naval architects should take place to define the proper input for the layout evaluation simulations.

This translation of the global allocation to a space specific allocation is made during the automatic generation of simulation models. For the purpose of demonstrating the method, a simple allocation of activities to marines and spaces is performed. This allocation method allocates the first eight marines to the first available MAR-8 cabin, and take place in the first landing wave. Likewise, the subsequent eight marines are allocated to the subsequent available MAR-8 cabin, and take place in the first available landing wave.

4 Test case results

In this section the results of the remaining steps will be discussed. First, Section 4.1, will discuss the results of the layout generation (step 4), followed by the results of the layout evaluation (steps 5 to 8) in Section 4.2. Subsection 4.3 will look back at the required and gained insight for the notional LPD test case and propose some design variations to improve the gained insight.

4.1 Step 4: Arrange spaces in a layout

As described in Sections 2 and 3, WARGEAR is used to generate detailed layout plans based on the functional arrangement given in Section 3.2. In total 520 detailed layouts have been generated in approximately 20 minutes by WARGEAR. In Figure 6 a histogram of the objective scores A_j, see Section 2.1, is given. Since the objective function is minimised, the most preferred detailed layout, from an area performance point of view, corresponds to the most left bin in the histogram. In this run, the most left bin contains only one detailed layout. Although this detailed layout still falls 110 m^2 short of the total required area of all spaces, this layout will be further investigated because only 1.2 m^2 per space is missing on average. Additionally, a histogram of the discrepancy between the RA and AA for each space in this layout is given in Figure 7. This histogram shows that most spaces meet or even overshoot their required area, while only a few spaces are problematic, e.g. one space falls $7m^2$ short of its RA. The latter spaces might prove challenging to be corrected manually.

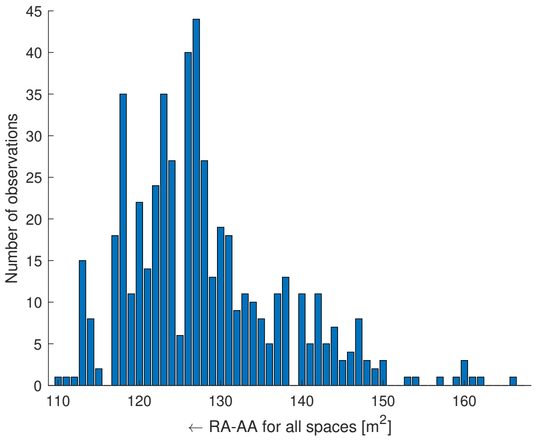


Figure 6: Histogram of the objective scores for all 520 generated designs

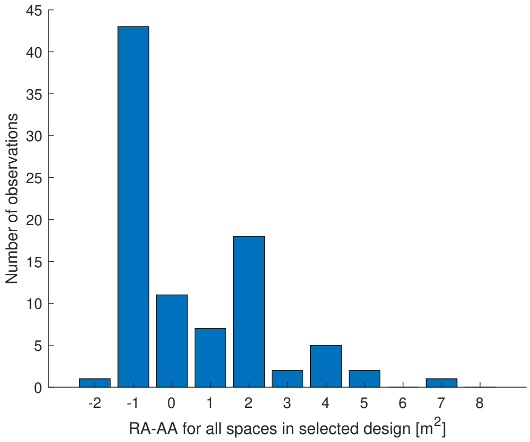
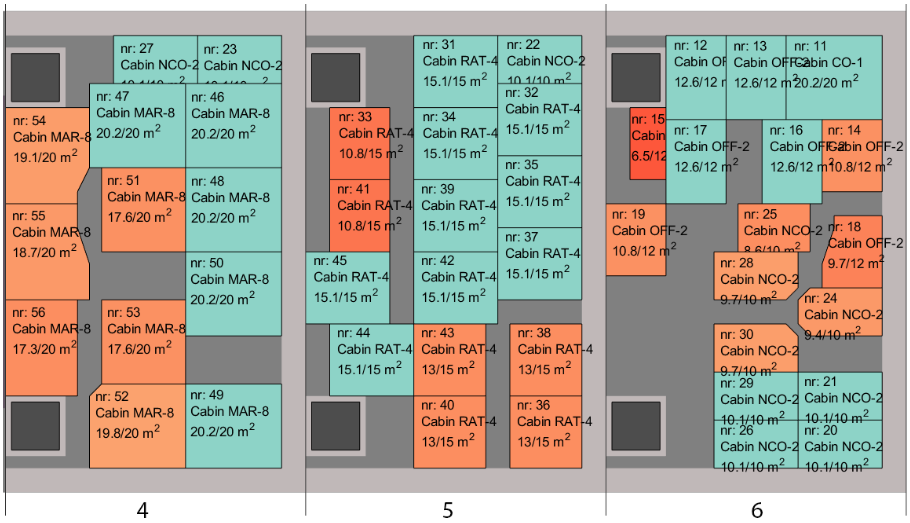


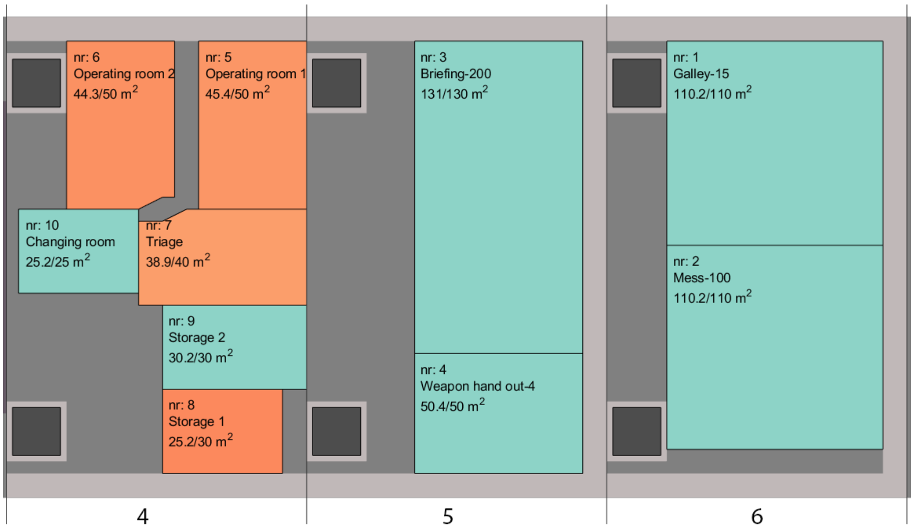
Figure 7: Distribution of the discrepancy between RA and AA for the selected design

Subsequently each deck is further analysed, starting at the upper most deck. Since the deck 2 has not been further arranged by WARGEAR, this deck will not be shown here. At deck 4, shown in Figure 8a, most spaces meet their RA. However, to ensure connectivity of all spaces to passageways (shown in light grey), area is reserved from spaces. For instance, area is reserved from the spaces 51 till 56 in compartment 4. Since there is also area available and some spaces are redundantly connected, e.g. spaces 53 and 54, naval architects are likely able to manually change the arrangement of the aft compartment, such that all spaces meet their required area. Similarly, in compartment 5, the spaces 33 and 41 are redundantly connected, and the available area aft of these spaces can be used to manually correct the layout generated by WARGEAR. Likewise, compartment 6 has significant area available to solve the insufficient area of space 15, for instance. To show how naval architects might translate a detailed layout generated by WARGEAR into a more feasible General Arrangement Plan (GAP), Figure 9 shows the manual arrangement of deck 4.

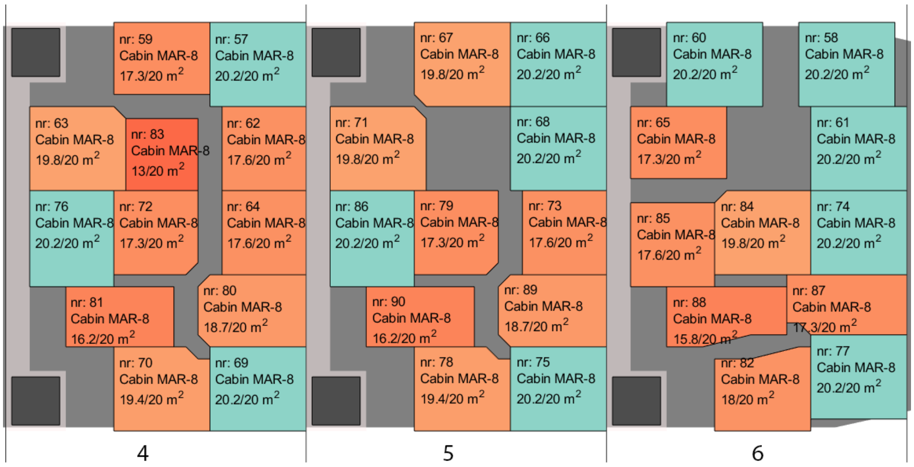
The detailed arrangement of deck 3 is shown in Figure 8b. Although some medical facilities don't meet their RA, sufficient area is available to manually produce an improved layout. Also, the amount of available area indicates that the Medical Facilities functional block, as shown in Table 4 and Figure 17, has been oversized. Therefore naval architects might utilise some the area in compartment 4 for other purposes, e.g. to arrange exhaust stacks.



(a) Deck 4



(b) Deck 3



(c) Deck 1

Figure 8: A more elaborate study of each arranged deck of the selected detailed layout.

Figure 8c shows the arrangement of deck 1. Compartment 4 and 5 are almost equally arranged. Although it is not immediately clear how to manually change the arrangement of spaces such that all spaces meet their required area, it is obvious that space 83 in compartment 1 will not meet its RA. The arrangement on deck 4 allows additional spaces to be arranged, certainly in compartment 3. Therefore space 83 might be reallocated to deck 4 to improve the overall objective score of the layout. Thus, the layout generation provides insight that on the lowest deck maximum eleven MAR-8 cabins of $20m^2$ can be arranged. To further improve the detailed layout plans for the given functional arrangement, the gained insight can be used to improve the allocation of spaces to compartments, which is part of WARGEAR's input.

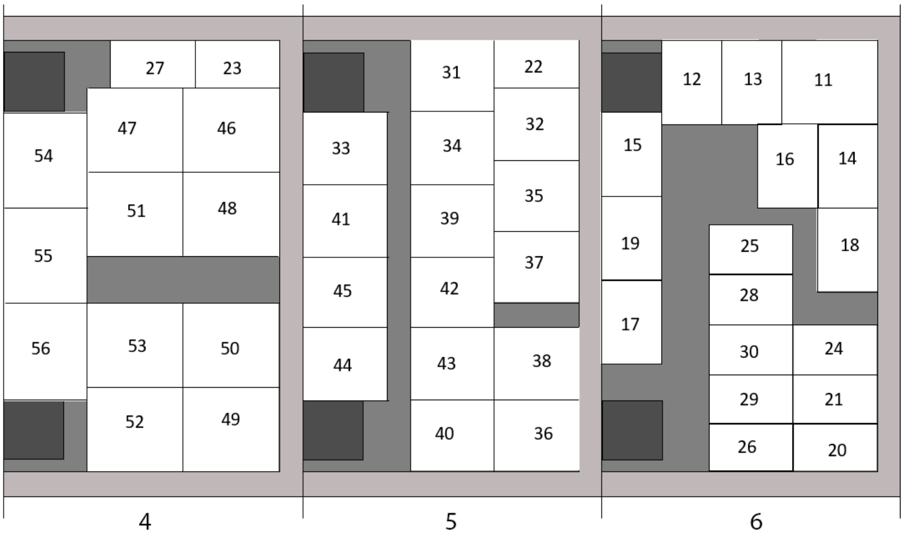


Figure 9: A manually created layout plan of deck 4, based on the layout generated by WARGEAR. All spaces meet their required area in the improved layout.

4.2 Step 5-8: Layout evaluation

The resulting layout is then used to route the processes, generate a queueing model, and simulate that model for the routed processes. In total 50 simulations are conducted, of which 32 are actually successful. Out of the 18 simulations that failed, 4 simulations failed due to limited capacity in one of the logical queues in a decision sub-system. The other 14 simulations suffered from a deadlock. For the purpose of this demonstration the failed simulations are omitted from the dataset and the analysis is continued with the 32 remaining simulations of which the convergence is presented in Figure 10. The convergence metric used is based on the total time to completion (TTC) of the simulation defined as the time between the first and the last event. The metrics used to compute the convergence are the procentual change in the mean and standard deviation of the TTC for an increasing number of simulations.

An outlier analysis is conducted on the TTC of the 32 simulations resulting in four outliers based on their value being three times the scaled median absolute deviation away from the median of the dataset. The outliers are visualised in Figure 11 and are all located on the right side meaning that they are slower then the median simulation.

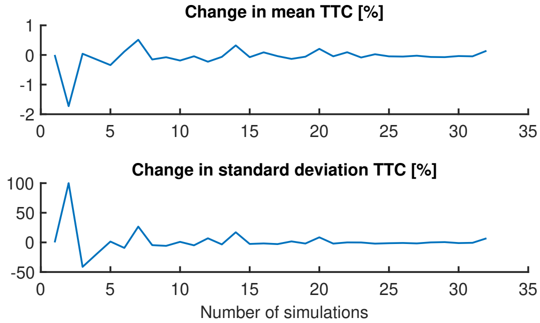


Figure 10: Convergence metrics for 32 simulation dataset.

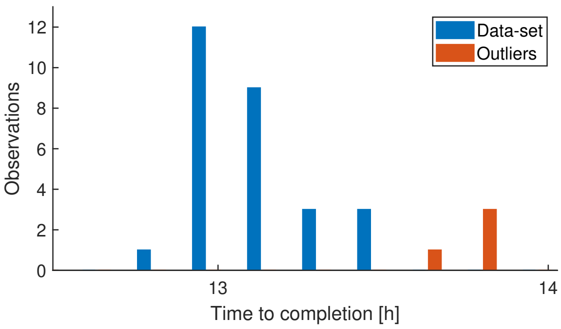
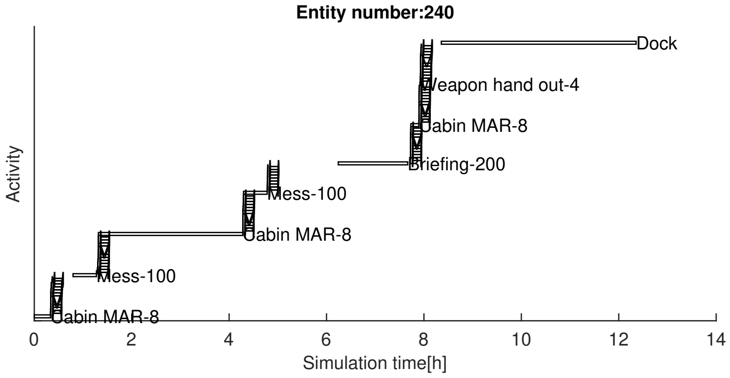
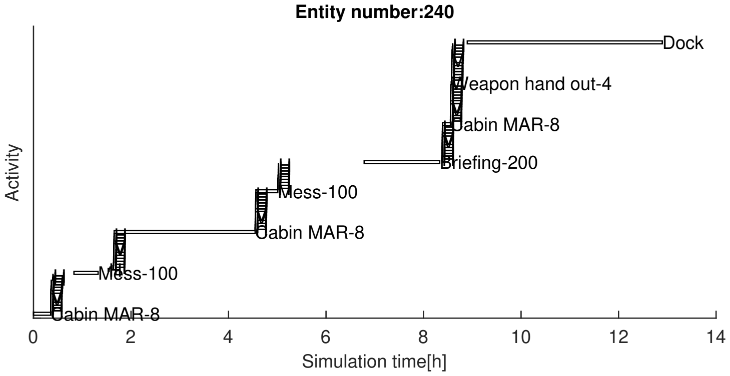


Figure 11: Distribution of the total time till completion for the 32 simulation with the outliers highlighted.

To explain the difference between the median and the outliers the processes executed by the entities are visualised using a Gantt-like chart. Figure 12 shows the process flows for two entities in both the median simulation and an outlier simulation. Figure 12 shows that in the outlier simulation the entity requires more time to complete his process. One of the things to note is the gap when leaving the mess the first time for the outlier simulation indicating congestion in the logistics around the mess.



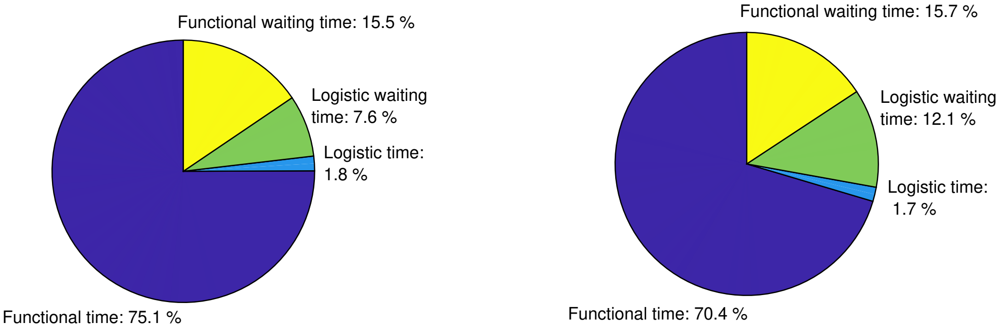
(a) Entity 240 in a median simulation.



(b) Entity 240 in an outlier simulation.

Figure 12: The process flow for a specific entity in a median simulation and for an outlier.

The gaps in the figure are times the entity has to wait because the next system in it's path is unavailable. To get a better view of how the time of the entities is spent during the simulation, Figure 13 shows the time divided over four categories. The first distinction is made between the time spent for the functional activities and the time spent to move around the ship, the logistical activities. Furthermore these times are divided between the time that an entity is actually active and the time it is waiting because the system is unavailable. This subdivision helps gaining insight in the layout's performance, as high logistic times indicate an inefficient arrangement with a lot of movement. The logistic waiting time relates to a lack of capacity in the logistical systems and might indicate the need for larger passageways for instance. Figure 13 shows that the outliers have more logistic waiting time which matches with the observations from the Gantt charts.



(a) Duration divided for a median simulation.

(b) Duration divided for an outlier simulation.

Figure 13: The duration of an entity divided over four categories of logistical or functional time, busy or waiting. For the outlier simulation relatively more time is spent waiting in the logistics.

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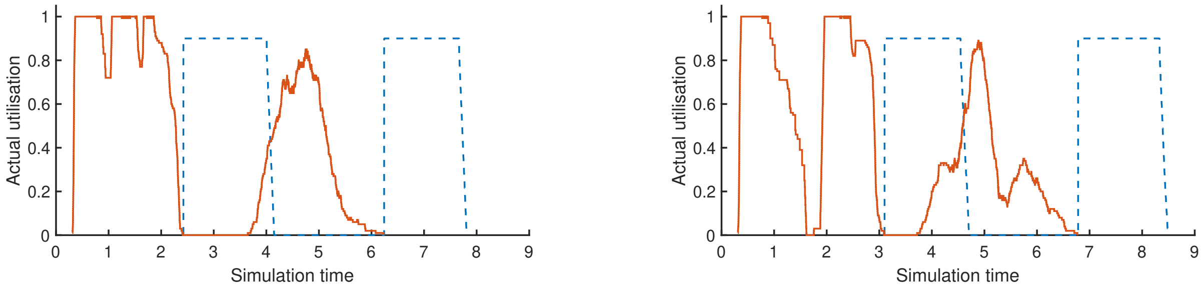
In order to understand what causes these outliers the results are studied and the utilisations of the mess and briefing room are plotted in Figure 14. This shows that for the outlier the mess first fully empties before new entities can enter resulting in a delay of the briefing. This is caused by a combination of elements, firstly the capacity of the mess is limited (100 entities) while all 360 entities try to go there at the same time. Secondly the capacity of the local logistics around the mess seems insufficient and no circulation restrictions are implemented at this stage. Lastly the current implementation of the simulation model uses a priority system that might contribute to this behaviour.



(a) The utilisation of the mess (red,solid) and the briefing (blue,dashed) spaces for the median simulation.

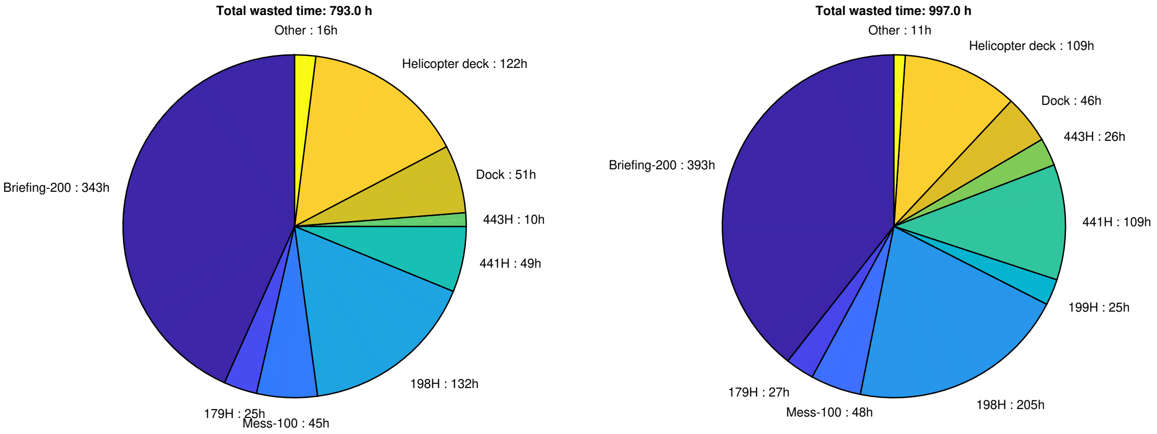
(b) The utilisation of the mess (red,solid) and the briefing (blue,dashed) spaces for an outlier simulation.

Figure 14: Utilisation of the Mess and the briefing room showing the different behaviour responsible for the outliers.

Lastly the functional and logistical waiting time in spaces of the layout is studied. The median and an outlier simulation are used to investigate where in the layout functional and logistical waiting time is created, see Figure 15a and 15b. The total waiting time for all entities is 793 and 997 hours for the median and outlier simulation respectively. Although Figure 15a and 15b show that the distribution of this waiting time is different for the two simulations, the waiting time is created in roughly the same functional spaces and passageways (indicated by the '*number* H' labels).

The following three observations regarding waiting times will be elaborated on next:

1. *Functional waiting time in the briefing room*. The largest contributor to functional waiting time is the briefing room. The functional waiting time is caused by congestion in the activities of entities prior to the briefing, as well as the required batch size. This can also be clearly observed in Figure 14.
2. *Functional waiting time in the helicopter deck and the dock*. Two reasons can be given for this function waiting time:
   (a) Like the briefing room, batch behaviour is modelled in the connectors, such that they only sail or fly when they are fully loaded.
   (b) The capacity of the connectors might not be perfectly matched with the speed of the LPD's internal processes. While the operational process is delayed early on, the afternoon wave takes place more rapidly. This causes entities to wait for the connectors to arrive.
3. *Logistical waiting time in passageways*. Logistical waiting time takes place in roughly the same passageways for all simulations. To help naval architects understand where this logistical waiting time is created, the network representation of the layout has been visualised with the actual layout in Figure 16. The locations in the network where waste is created are highlighted, while the marker size indicates how much waiting time is created. Also the functional spaces are indicated. The following observations can be made using this figure:
   (a) Most functional and logistical waiting time is created on deck three, in compartment 5 and 6.
   (b) The entrance of the briefing room and the weapon hand out are located at same location. This might cause a logistical bottleneck.
   (c) Significant functional waiting time is created in the mess itself. This might indicate that the capacity of the mess is insufficient to serve the 360 marines in the LPD.
   (d) Most logistical waiting time is created in the transverse passageway near the mess. This might be caused by the limited capacity of the mess, but also by insufficient space in the passageway itself.



(a) Waiting time per system in a median simulation.

(b) Waiting time per system in an outlier simulation.

Figure 15: Distribution functional and logistical waiting time for an average simulation.

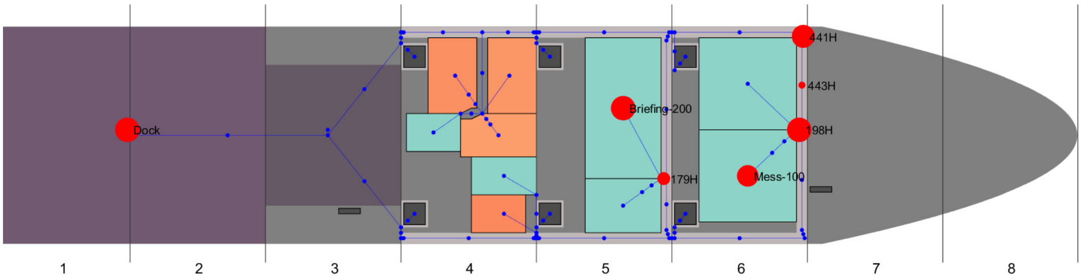


Figure 16: Arrangement of deck 3 in the selected layout with overlaying network representation, as well as an indication of locations where functional or logistical waiting time is created, based on the median simulation (Figure 15a)

4.3 Step 9: Reflection on gained insights

Step 9 has been described as a decision point in the exploration process, see Section 2.1. Besides demonstrating the proposed method, the test case was aimed to provide insight into possible bottlenecks in the operational processes and the relation of these bottlenecks to the layout of the notional LPD, Section 3. These insights point towards a number of improvements to the design. However, such changes should be thoroughly analysed to assess whether such changes would lead to other issues in the execution of the operational processes. The insight gained from step 4 till 8 of the method (Sections 4.1 and 4.2) is listed below, as well as a number of design improvements:

1. On deck 1 only eleven MAR-8 cabins can be arranged per compartment. This insight helps improving the allocation of spaces to increase the feasibility of the layout from an area point of view.

2. The entrance of key spaces, such as the briefing room, should be separated to reduce the logistical load on the passageways around these spaces.

3. The capacity of the mess, 100 marines, is insufficient to serve all 360 marines at once, which causes the briefing to be delayed and leads to a high logistical load on passageways. The capacity of the mess could be increased, or the processes of entities could be planned such that the load on the mess is reduced.

4. Passageways on deck 3 around the mess are logistical bottlenecks. This is caused by the limited capacity of the mess, although the width of passageways might have an impact as well. The latter should be thoroughly studied, by varying the width of passageways. However this might impact the feasibility of the layout from an area perspective. Hence, the interrelation between the processes and the layout.

Obviously more design variations could be proposed. However, the proposed variations should be sufficient to demonstrate that the integrated layout generation and evaluation method can be used to gain design insight for internal layout and process driven ships. Since every process will have a bottleneck, it is up to naval architects and decision makers to determine where the bottlenecks should be located.

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5 Discussion

To demonstrate the propose method, the conducted test case should provide insight into a LPD's layout and its operational performance, as well as lead to an understanding of the interrelation of layout and operational processes. As shown in Section 4.3, this demonstration has been successful. However, some issues were identified regarding the specific tools used in the method.

1. The automatic generation of simulation models accelerated the development of the queueing method vastly, however still some modifications are desirable to make the queueing method capable of evaluating layouts more efficiently and accurately. Amongst others the definition of the decision nodes in order to be able to handle multiple functional spaces at the same node. However modifying this, touches closely on one other area of improvement, the priority systems that is implemented to ensure that entities are processed in the right order to prevent deadlock, which is the situation where no further events can happen because entities are blocking each other in moving forward in their processes.

2. While WARGEAR is a near-real time layout generation method, and thus allows naval architects to study multiple input variations per day, the queueing based layout evaluation method requires approximately one day to generate and evaluate one variation. This mismatch in required run time raises additional questions. For instance, at what point in the layout generation process should layouts be evaluated from an operational point of view? Should layouts be feasible and balanced, prior to evaluating the operational performance of these layouts? Should the use of layout generation and evaluation methods be driven by the required design insight, e.g. on the interaction between a layout and the routing of logistical processes in that layout? Note this does not undermine the aim of this paper, i.e. to enable integrated, more detailed layout generation and evaluation earlier in early stage ship design. Indeed, a balanced detailed layout can be achieved relatively fast, and therefore sufficient iterations of the layout evaluation steps should be possible.

6 Conclusions and future research

During early stage ship design the most important design decisions are made. Therefore design efforts of naval architects focus on understanding the implications of requirements on the concept design. For 'internal layout and process driven ships' such as Landing Platform Docks (LPD), aircraft carriers, and cruise ships, the aboard operational processes have a logistical nature. Therefore these processes have a significant impact on the arrangement of the passageways, staircases, lifts, and spaces. To thoroughly understand the relation between the ship layout and the operational processes a concurrent ship layout generation and operational performance evaluation is required. Understanding this relation early in the design process is required to gain timely insights to inform the decision-making process.

However, the evaluation of operational performance is typically postponed to later design stages, where less changes to the design can be made. Since these changes are mostly related to the layout of the vessel, this paper proposed an integrated method for layout generation and evaluation. For layout generation the WARGEAR tool was used. WARGEAR is able to rapidly generate detailed layouts and provides insight whether all spaces fit and can be connected. A queueing based method was used to evaluate the operational performance of generated layouts. The method integration efforts focused on the automatic generation of a network representation of the layouts and the automatic simulation model development, to improve the usability of the method for naval architects. A test case was conducted to demonstrate the proposed method.

1. The test case showed the potential of the method to provide valuable insights for the design of internal layout and process driven ships. The method was used step by step in the test case. This indeed resulted in a number of design insights, and allowed for the proposal of design variations to improve the insight gained.

2. The use of the WARGEAR tool and the queueing based layout evaluation method showed that the feasibility of the layout from an area and of an operational process point of view can be concurrently evaluated. Therefore this design activity could be performed earlier in the design process to allow for larger changes to the design and meanwhile reduce the risk of necessary design changes later on in the design process.

3. Various visualisations of data were used to identify not only *where* in the layout issues arise, but also *why* these issues appear. This is considered to be key information for decision-making.

Future research includes:

1. The generation of network representations of layouts could be further automated to reduce the human input, both from a labour point of view as well as the risk for errors. Also, the location of space entrances should be reconsidered to reduce logistical bottlenecks. Further, future efforts can work on options to manually adjust the network representation to allow for smoother analysis of alternative networks of the same layout.

2. Improvement of the queueing based method to prevent deadlock. Further the method's efficiency and accuracy should be considered and evaluated. Comparing the queueing method with multi-agent methods might be an option.
3. An evaluation of the implications of the run time mismatch between the used layout generation and evaluation methods could be done. This should provide naval architects with guidelines how to effectively use the proposed method in real design cases.

Concluding, the integrated layout generation and evaluation method proposed in this paper will improve early stage ship design by helping naval architects to better understand the complex interrelation between a ship's layout and its operational processes. This understanding should allow the guidance of decision-making towards technically feasible and better performing designs.

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8 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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Appendix A - LPD Requirements

Table 3: Overall requirements for the notional LPD

Sizing requirements		**Logistic system requirements**		
			Length	*Width*
L_{oa}	120 m	Main passageway	[-]	2 m
B_{oa}	24 m	Secondary passageway	[-]	1.2 m
Compartment length	15 m	Main staircase	3 m	3 m
		Secondary staircase	3 m	0.8 m
Manning requirements				
Rank	*Number*			
CO [1]	1			
OFF [2]	16			
NCO [3]	22			
Ratings	60			
Marines	360			

[1] Commanding Officer. [2] Officers. [3] Non-Commissioned Officers.

Table 4: Space requirements for the notional LPD

Category	**Space name**	**Length**	**Width**	**Area**	**Capacity** [2]	**Number in design**
Medical facilities						
	Operating room	[-]	[-]	50	[-]	2
	Triage	[-]	[-]	40	[-]	1
	Storage	[-]	[-]	30	[-]	2
	Changing room	[-]	[-]	25	[-]	1
Operational spaces						
	Briefing room	[-]	[-]	130	180 [6]	1
	Weapon hand out	[-]	[-]	50	4	1
	Dock [1]	30	13.9	[-]	2 [3]	1
	Vehicle deck [1]	60	13.9	[-]	[-]	1
	Helicopter deck [1]	60	13.9	[-]	2 [4]	1
	Helicopter hangar [1]	60	13.9	[-]	[-]	1
Accommodation cabin area[5]						
	CO-1	[-]	[-]	20	1	[-]
	OFF-2	[-]	[-]	12	2	[-]
	NCO-2	[-]	[-]	10	2	[-]
	RAT-4	[-]	[-]	15	4	[-]
	MAR-8	[-]	[-]	20	8	[-]
Accommodation service area						
	Galley	[-]	[-]	115	[-]	1
	Mess	[-]	[-]	125	100	1

[1] marked spaces are *not* arranged by WARGEAR. [2] Capacity is given in number of marines, unless defined otherwise. [3] Capacity of the dock is two LCVPs. [4] The capacity of the Helicopter deck is two helicopters. [5] The number after the abbreviation represents the capacity of the cabin. [6] The briefing room has batch behaviour, such that the briefing only commences when 180 entities have arrived.

Appendix B - LPD Functional arrangement

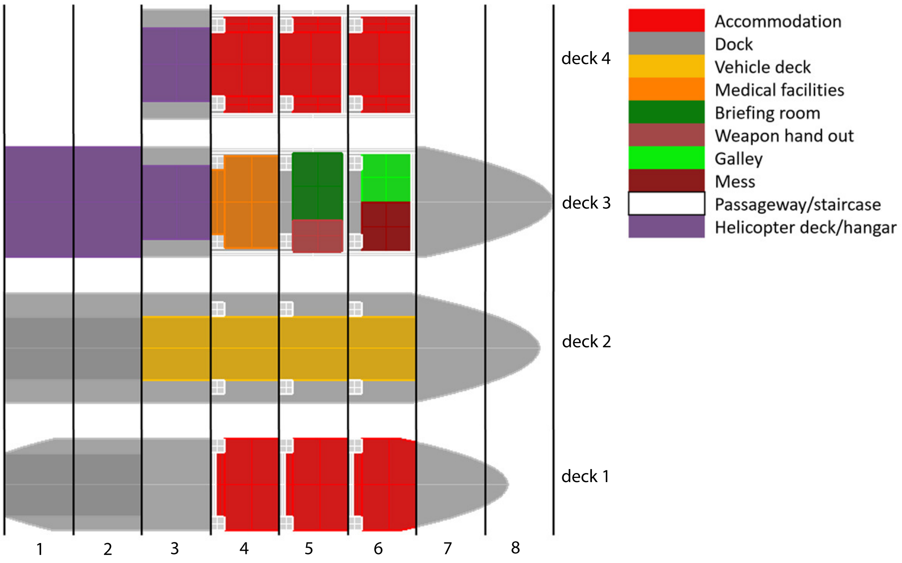

Figure 17: A functional arrangement of the notional LPD.

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