INTRODUCING OPERATIONAL INFORMATION INTO EARLY STAGE SHIP DESIGN USING QUEUEING NETWORKS

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SUMMARY

During the early stages of ship design a set of requirements needs to be identified, accounting for financial and technical feasibility, and operational effectiveness. This process of requirements elucidation creates a need for information regarding various design alternatives and their effect on the feasibility and effectiveness of the design requirements. When one considers internal layout and process driven ships, ships where the arrangement of spaces has a strong influence on the effectiveness of the ship's operational processes, a gap in available methods has been identified. This paper proposes a method based on queueing networks that allows a naval architect to study the effects of different arrangements on the execution of various sets of operational processes. Using this model a better understanding of the interaction between the ship's arrangement and its operational processes can be obtained. This understanding can improve the requirements elucidation process and can lead to the development of better design requirements.

1. INTRODUCTION

The European shipbuilding industry is known for its ability to design and produce low-run, complex, and highly specialized ships (Bruinessen et al., 2013). The early stages of design for these complex vessels focusses on elucidating an effective, technical, and financially feasible set of requirements (van Oers *et al.*, 2017). During this phase, the requirements need to be identified, combined, and subsequently evaluated in order to elucidate the most effective set of requirements. The elucidation of these requirements and selection of the most effective set is a form of decision process where various compromises have to be made. To support this effort, information is required to study alternatives and understand the influence of certain decisions on the performance of the final design. Due to the many interrelations between the design requirements, it is necessary to asses and compare complete design solutions consisting of a set of requirements, instead of a single design requirements (Duchateau, 2016). For instance, the decision for a diesel direct versus a diesel electric propulsion has an influence on the size and location of the exhaust stack, which in turn may affect the location of a flight deck. To fully evaluate this, a selection of options should be combined in a concept design and evaluated.

Multiple methods have been developed to support the process of finding and evaluating sets of requirements for feasibility and effectiveness, a process often referred to as requirement elucidation (Andrews, 2003). The goal of these methods is to provide information that support the dialogue between a naval architect and the problem owner in the decision process required to obtain an effective set of design requirements (Andrews, 2018). The applicability of these methods depends on what determines the effectiveness of a design since the information required varies strongly for different design problems. For instance, the TU Delft Packing approach (van Oers, 2011) deals with ships driven by weight, volume, or by their topside layout (See (Andrews, 2007) for a definition of topside layout problems). This method is able to provide insight into the relation between system selection and ship size, for example. On the other hand the Design Building Block approach can be applied to architectural or style driven design problems (Andrews and Pawling, 2003).

Although various methods exist for the various ship design problems, a specific ship design problem has been identified that requires a tailored design methodology. This type of design problem regards internal layout and process driven ships (iLPDs), where the relationship between the layout and the operational processes drives the design process. Although they share similarities with configuration driven ships as described in (Andrews, 2003; Andrews *et al.*, 2012), they represent a unique subset of this design problem. For configuration driven ships the arrangement of spaces is a design driver; however, for iLPDs the arrangement can be tied directly to the operational processes and focuses mainly on the internal layout. Therefore it is argued that the operational processes and their translation to an internal layout drive the design problem. The requirement elucidation process of these iLPDs requires operational information to evaluate this relationship. To support this effort this paper will: address the iLPDs design problem by proposing a method based on queueing networks, provide a proof of concept test case showing its benefits, and will finish by discussing considerations necessary for scaling up the proof of concept to ship scale.

2. THE DESIGN OF INTERNAL LAYOUT AND PROCESS DRIVEN SHIPS (iLPDs)

The authors define iLPDs as ships whose effectiveness is dominated by the performance of their various operational processes (Droste et al., 2018). For example, in aircraft carriers sortie rates or turnaround times are key performance indicators (Knight, 2009). While for amphibious assault ships the deployment and recovery times of a force of marines, or medical evacuation processes drive the design (Leopold and Reuter, 1971). Another example are cruise ships, where the vessel's layout and amenities are optimized to provide the best customer experience. These ships are often designed for processes characterised by numerous logistical activities with many people, large quantities of goods, and/or substantial materiel moving around.

These processes and their (logistic) activities have significant interactions with the layout. For example, a specific combination of layout and operational processes require large elevators, ramps, or specific locations for certain spaces or equipment to improve the process performance. In order to be able to identify these types of interactions and thus support requirements elucidation, a method able to evaluate the operational performance of a layout is required.

The evaluation of layout operational performance for requirements elucidation is challenging because both the amount of layouts to be considered is large and the design detail in these layouts is limited. Current design methods are limited in their ability to provide this information during early stage design as they are either too detailed or may not be detailed enough. High detail methods, such as multi-agent simulations, require large amounts of information and assumptions, making them unsuitable during early stage design, when design details and assumptions may change rapidly. Very low detail methods, on the other hand, such as gas-kinetic or regression models (Boulougouris and Papanikolaou, 2002), may provide a result that is too generic, thus limiting specific insights into the design case. Gas-kinetic models evaluate the flow of people in a layout based on densities and velocity changes over time. These models focus on analysing the capacity of a layout without considering individual processes or their performances (Glen and Galea, 2001). Therefore these methods may miss the interaction between processes and the effect a combination of these processes have on the layout. Regression models are based on large datasets and therefore less suitable for early stage design for these complex vessels as sufficient data and analysis of comparable layouts needs to be available.

Other industries outside of ship design have faced similar problems. The evaluation of hospital layouts, for instance, has been analysed using fuzzy logic by using rules to incorporate both logistic requirements as well as qualitative aspects such as easier hygiene management (Liu et al., 2015). The rules have been created based on expert input and the layouts are then created and evaluated manually. The amount of expert opinion required to get a consistent set of rules seems limiting, but the ability to combine the various layout requirements, both quantitative and qualitative requirements, is promising.

Furthermore, the domain of facility layout problems also provides promising relevant methods. Facility layout problems deal with the arrangement of facilities in a layout for a given set of objectives. An overview of multi-floor facility layout problems is provided in (Ahmadi et al., 2017). Within the overview the distance between two facilities is identified as a common part of the objective function. However they also note that only using the distance gives a linear approximation which neglects the waiting times that might occur at elevators for instance. Thus for facilities where transportation systems are limited or might be vulnerable to congestion, an evaluation based on simply distance alone provides limited insights

3. METHOD REQUIREMENTS

Based on this problem definition, the method should satisfy the following requirements:

- *Needs to evaluate processes given uncertainty*. The exact start time and duration of a process can vary for different instances. These small variations may have a downstream effect on the other processes that start sequentially afterwards or they may use the same physical space. This may result in variations in operational performance. For a robust design solution small changes in the process execution should not result in large changes in process performance. Therefore, if a wider range of design options is covered during the analysis, a more robust and holistic evaluation of the layout may be achieved. On the other hand, when the performance is highly sensitive to process variation, the method may reveal areas of high interdependency between the process and performance relevant for the naval architect to study in more detail.
- *Needs to identify different layout alternatives*. Given a set of required spaces and systems, the variations that can be made in the layout are related to the relative and absolute locations of these required spaces and systems and their connectivity. To be able to analyse this effect and understand the link between layout and process performance, both a change in connectivity and in distance between spaces needs to be evaluated as these provide insight into the quality of the locations.
- *Needs to capture the interaction between processes*. Multiple processes may occur at the same time and some processes might require the same space. Thus, space capacity might influence both processes, and interactions and interdependencies might occur.
- *Needs to be expandable*. Both the size of the layouts considered, as well as the number of processes might change over time or for different design problems. Therefore the tool should be expandable in both the number of processes and the size of the layout without becoming intractable.

- *Needs to support the design activity*. The work in this paper is focussed on the concept exploration phase; where the goal is to identify possible solutions to the problem and to assess the feasibility and effectiveness of these solutions. Such a solution involves a set of design requirements, a design, and a performance and cost evaluation. These three items help answer the questions: what is needed, can it work, and how good is it? The method should support answering these questions. Meanwhile this design phase is characterised by limited detailed information. At this point in the design process, a few high level design decisions are made and locked-in which have significant impact on the remaining design process (Niese et al.,2015). The method should be able to evaluate various combinations of requirements, while handling a low level of detail of both the layout and process information.

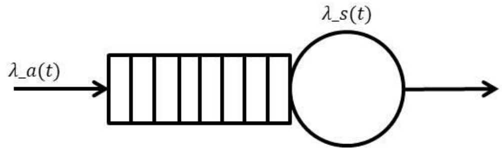
Results should help explain the relationship between process performance, the location of spaces and systems, and their connectivity. Results should also show how the interaction between the processes influences the performance and layout requirements. For instance, multiple processes might require the same system at the same time causing delays or capacity issues. These results will help a designer during the early design phases to evaluate design requirements and make more informed design decisions.

In order to satisfy these requirements a solution using queueing networks is proposed. Queueing networks are a common approach to evaluate operational processes in layouts. For example they have been used to evaluate workshop layouts where waiting times and congestion play an important role in the overall performance (Pourvaziri and Pierreval, 2017). By substituting the functional spaces in a ship with the production stations in a workshop and the people as entities moving through the model, a first idea of how queueing theory can be used to evaluate the operational performance of a ship layout can be established.

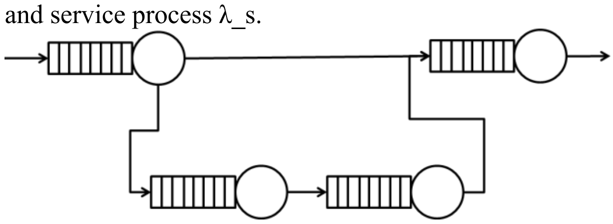
However, some challenges remain when directly applying this idea to the iLPDs problem. The first one has to do with transportation. For the ship arrangement problem this should be modelled as a space, rather than a resource consuming system. Furthermore, the routing of entities becomes a more complex problem, and the size and number of layouts requires a different approach. The following section will provide background on queueing networks, before addressing these issues by proposing a model architecture and a method. These will finally be tested in a case-study.

4. QUEUEING NETWORKS

Queueing networks allow a system to be described based on its capability to handle and process entities over time. It is based on a queueing system as shown in Figure 1(a), which has an arrival process λ_a, a queueing process, a service process λ_s, and a departure process. These processes are often modelled stochastically to realistically represent the uncertainty in processes (Brinksma et al., 2001; Mieghem, 2014). Queueing systems provide a means to evaluate the capacity of a service system by various performance metrics such as: waiting time, the time spent in the system, utilisation of the server, or number of entities in the queue. In this paper these metrics are used to gain insight into whether the systems aboard a ship have sufficient capacity to support the operational processes.



(a) A single queueing system with arrival process λ_a and service process λ_s.



(b) A network of multiple queueing systems.

Figure 1: Examples of a single queue system and a queueing network.

However, naval architects are more interested in the combination of these systems in a ship arrangement, necessitating a push towards queuing networks. A queuing network is the combination of multiple queuing systems (see Figure 1(b)). Queueing networks enable the analysis of more complex systems with various sub-systems each with their own service processes. On top of the metrics a single queueing system can provide, queueing networks allow for the analysis of routing and scheduling problems, and the analysis of congestion and blocking of sub-systems and their effect on the system.

Queueing networks can be open, closed, or a combination thereof. An open queueing network allows entities to arrive from outside the system, and thus the number of entities in the system varies over time. Closed queueing networks, on the other hand, have a constant number of entities present in the network. A combination has parts of the network where the number of entities are constant while another type of entity varies over time.

Another distinction is the capacity of the network. In a finite capacity network, the network will congest if the number of entities approaches the maximum capacity of the network. While in an infinite capacity network this phenomena does not occur. Finite capacity networks can be used to analyse system interactions based on capacity constraints or population sizes. For instance delays occurring because to many entities from multiple processes require the same system. Infinite capacity queueing networks are used to find the flows or routings in a network and size components accordingly.

Finally, queueing networks can be solved analytically, heuristically, or by means of simulations. Analytic solutions are often only achievable for more standardized forms of queueing networks (Mieghem, 2014), while heuristics are slightly more widely applicable. Simulations tend to be more computationally expensive and can be more time consuming due to the required modelling effort, but allow more freedom in the network definition and are able to capture more of the transient behaviour (Kouriampalis, 2019).

Queueing networks are widely applied in operations research. Applications vary from computer networks (Gebali, 2015) to waiting queues and scheduling in hospitals (Helm and Van Oyen, 2014; Marynissen and Demeulemeester, 2016), to the analysis of large scale traffic scenarios (Charypar, 2008) or to the arrangement of equipment in a flexible workshop (Pourvaziri and Pierreval, 2017). They are typically used to determine the throughput of the network (data, patients, vehicles, or work orders) and the costs involved with accomplishing that, such as network hardware, size of medical staff and facilities, amount of roads and intersections, or amount of equipment and rearranging costs. Pourvaziri and Pierreval (2017) discuss arranging equipment in a pre-defined grid of a workshop. This has similarities to arranging spaces in a ship in the grid of bulkheads and decks. However the travel routes such as passageways and staircases are pre-determined in the workshop, while in a ship due to the space limitations they are a part of the arrangement process.

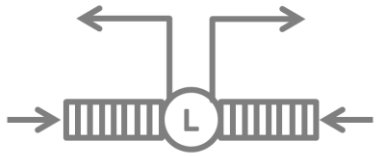
Only a few applications of queueing theory in the ship design field exist, as most are related to ship production or operations. For example queueing theory has been used for production planning of sections in various workshops at a shipyard (Dong *et al.*, 2016), offshore supply chain optimisation (Hellum, 2015), or for port terminal operations (Legato and Mazza, 2001). For ship design specifically, Kouriampalis (2019) applies queueing theory to elucidate the requirements for UXV facilities aboard a mothership. The capacity of these facilities is determined by analysing UXV's operational processes using a queuing network. However none of these applications look into studying the ship layout itself, especially the internal layout with the arrangement of spaces, passageways, and staircases with respect to the operational processes.

Thus, there is potential for applying queueing networks to the evaluation of layouts in early stage design. However, in order to fit the iLPDs design problem specifically, a model architecture needs to be defined first.

5. MODEL ARCHITECTURE

In order to model the layouts as a queueing network three types of sub-systems are defined: a functional sub-system, a logistical sub-system, and a decision sub-system respectively which are visualised in Figure 2.

(a) A functional subsystem used to model the spaces with functional activities.



(b) A logistical subsystem used to model for example passageways or staircases.

(c) A decision subsystem used to connect the other subsystems and model the routing of entities through the model.

Figure 2: A schematic representation of the different subsystems defined in the model architecture.

- *Functional sub-system*. The functional sub-system is used to model spaces in the layout where functional processes occur, such as cabins or mess halls. This sub-system consists of a server and a queue with a capacity equal to the service capacity and holding capacity of the space. For example, a mess with ten seats and space for five people waiting is modelled as a server with a capacity of ten entities and a queue with a capacity of five entities.
- *Logistical sub-system*. The logistical sub-systems are the passageways, stairs, and lifts. These logistical sub-systems consist of a server and two queues. The server has a capacity based on the size of space, and a service time based on both the size and number of entities in the system. An exponential relation is used to model the impact of the number of people in the system on their transit velocity (Mitchell and Smith, 2001). This exponential relation can help elucidate complex responses in the passageway. For example, increasing the passageway length will increase the travel distance and thus travel time, while it will also decrease the density of users and therefore assign higher travel speeds which decreases travel time. The queueing network is expected to capture not only this trade-off, but also its influence on the broader ship layout system. Lastly, the two queues enable monitoring the different directions of travel separately. This allows

the method to account for counter-flow by adjusting the algorithm based on the mix of direction present in the logistical system (Mitchell and Smith, 2001).

- *Decision sub-system*. The decision sub-systems are used at the intersections, doors, and other interfaces between systems where directional decisions need to be made. They consist of a single server with infinite capacity and a service time equal to zero. It is assumed that making a decision is considered instantaneous and is not limited by the amount of entities. The decisions nodes are therefore mainly used to organise the routing of entities throughout the ship's layout. This routing can be organised in multiple ways, such as using simple predefined paths, or more advanced probabilistic path-finding methods such as Markov based methods (Kana and Droste, 2019).

The model structure itself is made with the servers and queues, while the moving entities are the ship's crew or passengers. These people have predefined processes which are defined in the attributes of the entity.

This modelling architecture requires limited modelling effort and improves expandability, which are both required to create a method to support the requirement elucidation process. The structure with separate functional sub-systems also allows for changes in the analysed processes, as the process variables are stored in those functional sub-systems. For the analysis, this modelling architecture allows specific metrics to be calculated, such as the average queue length in a specific direction of a passageway.

Lastly, the service time in the logistical systems is dependent on both the size of the system and the number of entities in the system. In this situation, solving the queueing network analytically becomes infeasible and a simulation based approach is thus pursued. This also enables the ability to capture transient behaviours where analytic methods usually focus on steady state results only. Furthermore an infinite capacity, open queueing network is used to allow a more free definition of entities and task schedules suitable for the current phase of method development.

6. THE QUEUEING-BASED METHOD

The previous section described in general how queueing theory is used to model layouts and analyse various processes aboard iLPDs. This section describes the detailed process used in this method to do the analysis. This process consists of five steps, as presented in Figure 3.

i. *Receive set of processes*. The first step identifies and collects the operational process related information. This information includes the processes, their activities, as well as their performance metrics, such as duration and throughput.

ii. *Define spaces and systems.* The second step defines all spaces and systems required to study the operational processes. Modelling only the parts of the layout required for the analysis limits the information necessary and allows for earlier use of the method. As the aim is to study the effect of layouts on the operational processes, all the individual building blocks and the envelope in which they are placed are defined separately. This enables the naval architect to vary the layout and study the effects of these changes. The information required for this depends on how these layouts are created. For example, in this case study a small set of layouts is manually drawn; however, layouts generated in other methods could be used as well, for example: (Andrews and Pawling, 2008; van Oers, 2011; le Poole, 2018).

iii. *Create layout representation*. Step three creates the layouts with the information collected in the previous step. The method chosen to generate layouts depends on the number of required spaces and the number of alternative layouts to be considered. Because this method is developed in the context of early stage ship design, many alternative layouts are expected. This favours the use of an automated layout generation tool, for instance one based on the work presented in (le Poole *et al.*, 2019).

iv. *Assess operational processes via queuing model*. The fourth step evaluates the layout for the operational processes defined in step 1, using a queueing model. Thus, a model is needed that describes the layout, using the building blocks defined in the model architecture section. The process times at the various servers are defined according to the processes in step 1. For these process times probability distributions are used to incorporate the variation of these processes in the simulation and improve the robustness of the answer. The process time is drawn from a normal distribution with a lower limit at zero to prevent negative times. Thus, in the process definition a mean and standard deviation are provided instead of a list of times. The people are created using the entities and processes are assigned to the entities attribute in the form of a routed path. Eventually the model is simulated for a set number of executions to create a distribution of results, which is then checked for convergence.

v. *Combine results to study performance and effectiveness*. The goal of step five is to identify the various effects of changes in the layout on the process performance, taking into account the interactions and uncertainties in the processes. To do this, the results of various simulations are compared to identify better arrangement characteristics. It is also necessary in this step to check the execution of the simulations and verify the results of the individual simulations.

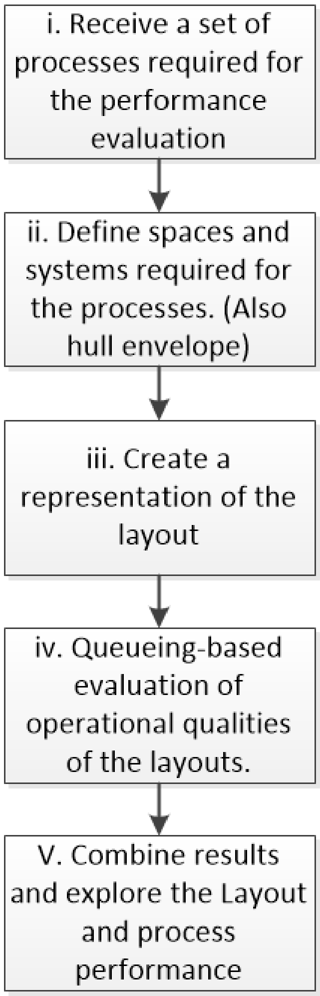


Figure 3: The flowchart showing the steps taken in this proof of concept to demonstrate the queueing-based method.

For verification and validation three types of results can be studied. First, the qualitative results from a single simulation can be examined to assess the validity of the simulation of that specific layout and to get a qualitative understanding of how such a layout functions. These results can be converted to animations to create insight in the functioning of the model. Second, the distribution of results from a single layout or scenario can be studied to identify outliers, or to identify the specific combinations of input variables leading to such behaviour. These distributions also provide an overview of the relation between a specific layout with its potential process performance. Finally, evaluating distributions from multiple layouts allows for the comparison between layout features without factoring in specific process variation. This will help in gaining insights into the effect of specific layout changes on the process performance.

In order to quantitatively study the distribution of results, four statistical values are calculated: the mean, standard deviation, kurtosis, and skewness. The kurtosis value compares the shape of the distribution to a bell shaped normal distribution, where a value of 3 corresponds to a normal distribution. A value lower than 3 represents a flatter distribution, and a value higher than 3 corresponds to a more peaked distribution. The skewness is a symmetry value for distribution and can be used to find an imbalance in the results. A positive value indicates that the right tail of the distribution is longer, while a negative value indicates the opposite. Together these four values help provide targeted and relevant insight of the model for the naval architect.

7. THE CASE-STUDY

This section presents a case-study to demonstrate the proposed method. The layout analysed in the case-study consists of a cabin, a mess, optionally a garbage store, and one or two passageways. The layout is evaluated for the simple process of having a meal at the mess hall, with a small variation adding a garbage disposal step. The size and complexity of the case-study has been limited to two processes and two layout variations to ensure tractability at this stage of method development. Comments on scaling the method to full ship scale are provided in the Discussion.

7.1 DESIGN OF EXPERIMENTS

The case-study compares three scenarios:

i. A baseline scenario where all spaces are connected with a single passageway and one process occurs.
ii. A double passageway scenario, where the passageway capacity is doubled by adding a second passageway.
iii. A two process scenario where an additional garbage disposal process is included.

The layouts of the three scenarios are given in Figure 5.

Two hypotheses are tested regarding these scenarios.

1. *Doubling the passageway capacity is expected to reduce the time to completion by roughly half.* This hypothesis tests a change in the layout. This change is also expected to have an influence on the duration of individual processes.
2. *An additional process will increase the spread in the distribution of the duration times*. This hypothesis tests the influence of adding an additional process. The spread of distribution of duration times is expected to increase because only some of the people will stop by the garbage store and the order in which this process happens varies. This will cause a variation in the people using the passageway and therefore increase the variation in the process duration.

7.2 APPLYING THE QUEUEING BASED METHOD

For step 1 of the method, two processes are studied: one involving people going for a meal in the mess, and the second involving taking out garbage from the mess to a dedicated garbage store. Both processes, their activities, and the variables for each activity are shown in Figure 4. The case-study uses an open queueing network as a pre-defined number of people enter the network, execute either of the two processes and then leave the network. In this case-study 50 people are simulated. For the first two layouts a single process is evaluated, but for the third layout two processes are considered. For the third scenario, it is assumed that each person has a 10% chance of being assigned to the garbage process. From the results it has been observed that this results in somewhere between 1 and 14 people taking out the garbage. This assignment is done at the initiation of the simulation based on a binomial distribution.

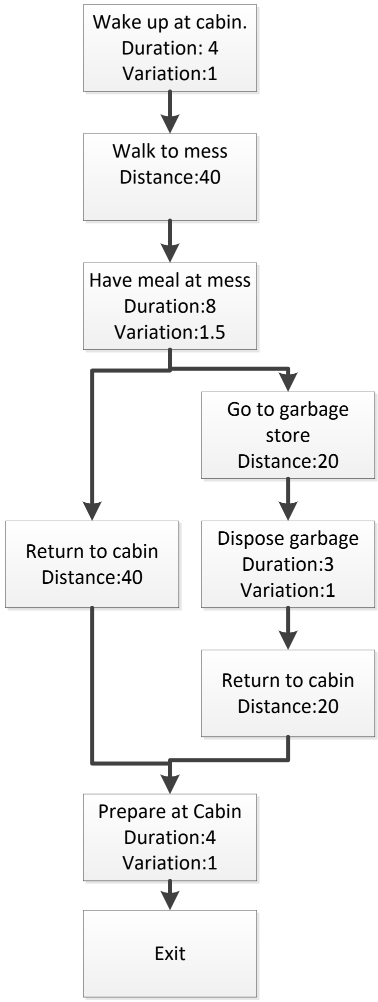


Figure 4: Process flow of the two processes used in the case study with parameters used for various activities in minutes or meters. The left column is the standard process, while the right column shows garbage disposal variation.

The second step of the method defines and identifies the spaces in the ship. Given the processes defined above, cabins, a mess, 1 or 2 passageways, and an exit are required. All spaces have a capacity defined as the maximum number of people they can accommodate. The passageway and cabin capacity are set at 10 people and the mess at 15.

In the third step these spaces are manually arranged in two different required layouts as shown in Figure 5.

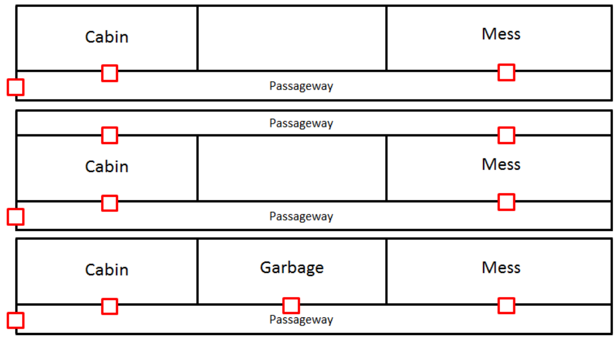


Figure 5: The layouts for the three scenarios of the case-study, the garbage store has only been shown in the third layout where the garbage process is added.

In the fourth step the models are created and the simulations are carried out. A diagram of the generated model for the first layout is provided in Figure 6. The simulations were run in Simulink using the SimEvents toolbox (Mathworks, no date). The queueing model's simulations were calculated using event-based time and the simulations ran until all events were completed. Each model was simulated multiple times to obtain a distribution of results accounting for the stochastic input process variables. 1000 simulations were run for each model. The variations and mean values for the distribution were checked for convergence, as shown in Figure 7.

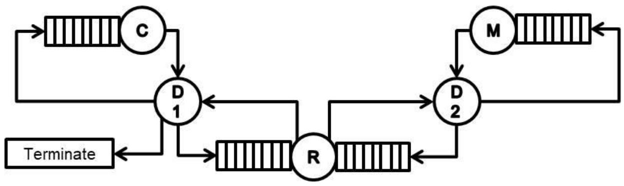


Figure 6: A diagram representation of the queueing model of the first layout.

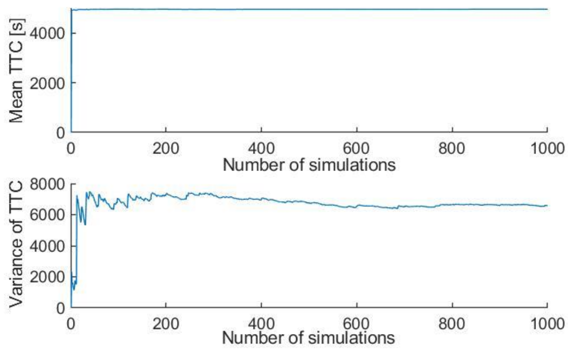


Figure 7: The convergence of the mean and variance of the Time-to-completion values for the first layout show that 1000 simulations are sufficiently representative.

The fifth step analyses the results of the case-study. Before examining the hypotheses above, the results will be studied to assess the validity of the results, and to do a verification of the model. Figure 8 shows a part of the sequence viewer with results from the simulation of the first layout. This sequence viewer presents the various activities taking place in parts of the queueing network as events starting at a specific time with a duration. By observing the sequence viewer and tracing the processes of the displayed entities, such as the one marked with red wide underlining, the functioning of the model can be qualitatively assessed. This method of qualitative assessment is supported by (Pedersen *et al.*, 2000; Senderovich *et al.*, 2015). As existing data did not exist for this case study, comparison with existing results was not possible. As the size of these models is limited, this method of manual assessment is considered sufficient for verification.

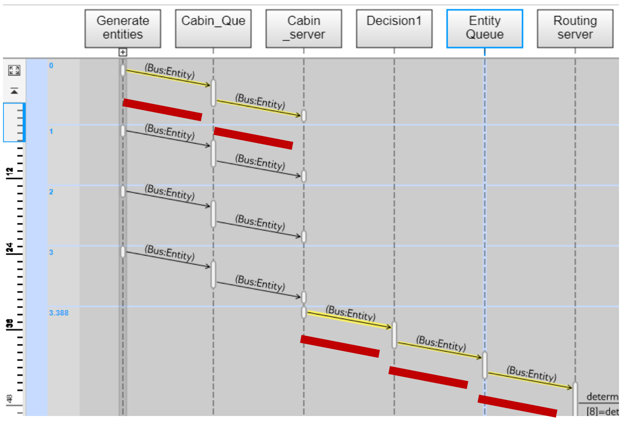


Figure 8: A sample of Simulink's sequence viewer, an overview that plots the time on the vertical, the subsystems on the horizontal, resulting in the entity's paths with one highlighted in the example. This enables checking both the order of operations as well as their duration to help qualitatively verify the model.

7.3 RESULTS OF HYPOTHESIS 1: A CHANGE IN LAYOUT

After qualitatively verifying the three models via the method depicted in Figure 8, their results can be used to test the hypotheses. The first hypothesis regards the effect of altering the layout on the overall time-to-completion. Figure 9 shows the distribution of the time-to-completion values for scenario one with the single passageway and scenario two with the double passageway. From the figure two observations can be made. First, doubling the passageway capacity does not half the time it takes to execute all processes. Second, the distribution of the time-to-completion values for the single passageway has a different shape than the distribution of the double passageway layout.

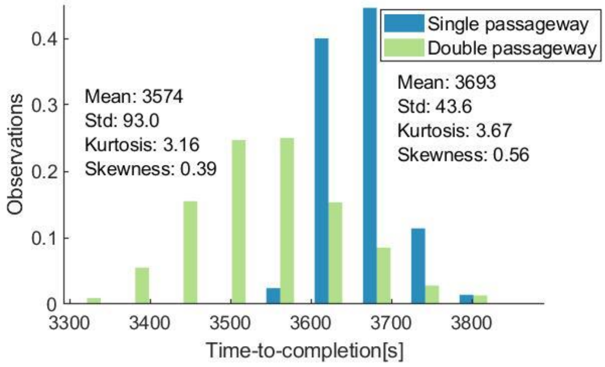


Figure 9: Comparison of the distributions of the time-to-completion for the first and second layout.

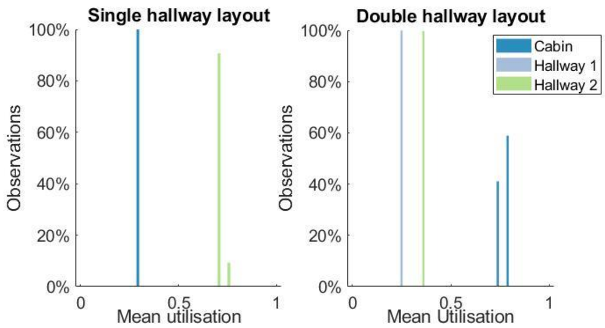


Figure 10: Visualisation of the average utilisation of the cabin and the passageway for the set of simulations and both layouts. A shift in bottleneck can be seen from the passageway in the single passageway layout to the cabin in the double passageway layout.

The decrease in time-to-completion observed between the first and second layout can be explained by evaluating the average utilisation of the cabin and the passageway. Figure 10 shows the average utilisation of both the cabin and the passageways for both layouts and the 1000 simulations. Two observations are to be made. One, the utilisation of the passageway for the single passageway layout is relatively high, given that this is an averaged value. It can be concluded that for the single passageway layout the bottleneck is most likely at the passageway. Second, while the passageway utilisation for the double passageway layout drops, that for the cabin raises. Adding a second passageway therefore shifts the bottleneck from the passageway towards the cabin.

The second observation is the difference in the shape of the distribution of the single passageway compared to the double passageway. Comparing the distribution of results in Figure 9 it can be seen that the results of the double passageway better resemble a normal distribution while the results of the single passageway are more concentrated. This can be seen from the higher kurtosis value and the lower standard deviation for the single hallway configuration. To further investigate this the individual durations, the time it takes a single entity to complete the simulation, are plotted in Figure 11.

The distinct peaks in the results for layout one represent the almost batch based manner in which entities are able to travel along the passageway. Each of the peaks corresponds to the next 24 entities in the simulation, meaning the first peak corresponds with the individual durations of the first 24 entities in each of the simulations. The specific number 24 originates from the passageway capacity and the three peaks from the 50 entities using the passageway in batches of 24 (2*24 and 1*2).

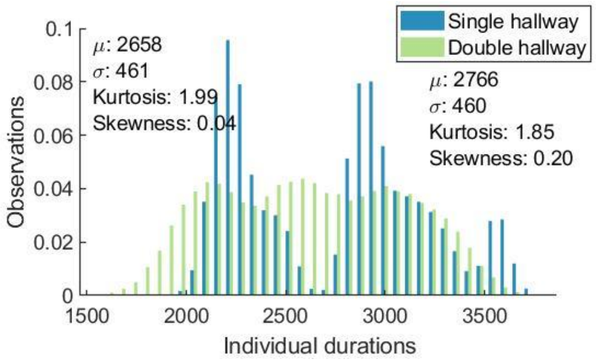


Figure 11: Comparison of the distribution of the individual durations of the entities in the simulation. Bar height corresponds to the number of observations for a specific interval of durations.

The results of the double passageway for the individual duration are more smooth caused by the increase in passageway capacity. This indicates that the two passageway scenario represents a better balanced layout where the various capacities are better balanced with each other.

7.4 RESULTS OF HYPOTHESIS 2: A CHANGE IN OPERATIONAL PROCESSES

The second hypothesis stated that adding the second process of the garbage store will increase the spread in the results. Figure 12 compares the results for scenario one and three. The additional process increased both the average time-to-completion by roughly 100 seconds, and also the spread in results by increasing the standard deviation. The kurtosis indicates a more even spread. For scenario 3 the kurtosis is almost 3, indicating that the distribution is very close to normal. While for the first layout the distribution is slightly peaked. The skewness value for scenario 3 is 0.19, which indicates a slight imbalance to higher values; however, it is lower compared to layout 1. In this case both kurtosis and skewness indicate that the results for the two process layout is more normal distributed. For comparison these values have also been provided in the Figures 9 and 11, with results for the other scenario.

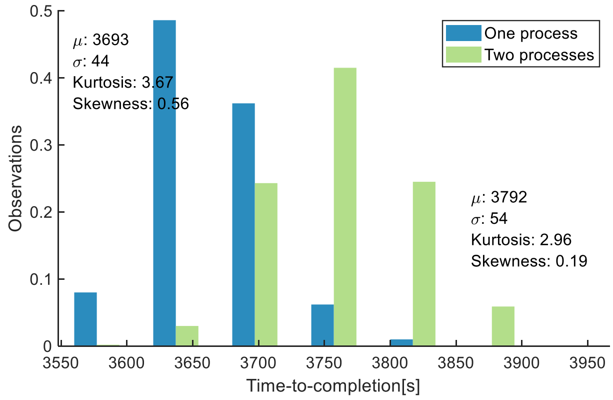


Figure 12: Comparison of the distribution of the time-to-completion for the first and third layout.

Furthermore, when individual durations are considered (see Figure 13) it can be seen that the distribution of the results is similar to a normal distribution with a kurtosis value of 3.09. Although the mean value of the distribution increased, the standard deviation decreased, meaning that more results end closer to the mean. Finally, the distribution has a negative skewness which indicates that more extreme values are located in the lower range, left of the mean.

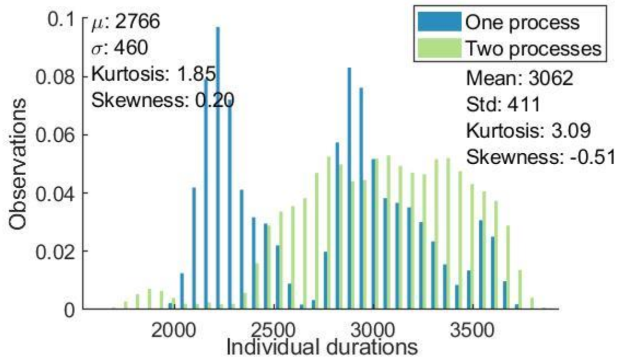


Figure 13: Comparison of the distribution of the individual durations for the first and third layout.

Thus, the results of the second comparison show that the interaction between processes increase the duration of the process, but will improve predictability of the total time-to-completion. For individuals it can be seen that it is more likely to find extreme values for shorter durations due to the negative skewness. Thus, adding the extra process decreases the spread in results for the individual entities, but increases the spread for the overall duration of the scenario.

8. CONCLUSIONS

The case-study presented in this paper demonstrated the potential for the use of queueing networks as a method for the analysis of operational processes in layout during early stage ship design. The results presented showed both insights in the process performances (individual duration, time-to-completion, and utilisation) as well as the effect of layout changes.

To get more robust results and to deal with the uncertainty in start time and duration, stochastic values have been used for these input variables. These stochastic inputs result in a distribution of results and four metrics have been used to measure and analyse the shape of these distributions.

Furthermore the results of the comparison between the first and second layout demonstrated the ability of the method to identify the effect of layout changes on the process performance. Due to the capacity limits of the cabin the reduction in time-to-completion decreased by only 40% while the passageway capacity was doubled. Lastly, the interactions between processes have been studied by comparing the first and third layout. Although an observable change in results was found, no clear cause or effect has been identified. Therefore further developments are required in visualising and evaluating these interactions.

Although the method presented has the potential to enable naval architects to explore layouts and their processes earlier in the design process, which would be a valuable improvement on current practice, further developments are required to implement the method in practical early stage design.

9. DISCUSSION

Although the method was demonstrated in a small case-study, some aspects require further development. The first point of attention is regarding the scalability of the model. The current models are created manually, which requires significant effort and introduces room for modelling errors. While for larger, more relevant, layouts the size of the models increases rapidly and with that the modelling effort. Furthermore, the lack of structure in the models makes it more laborious to scale. Thus, introducing a grid-based model layout or automating the model generation will be considered for future models. A grid-based approach allows the model to be setup more generically, while using the inputs it can still be adopted to specific layouts by deactivating unnecessary parts of the model.

The second point is regarding the implementation of the different subsystems. The current networks are infinite capacity networks due to the way the decision nodes are setup. For this smaller case-study this gives a reasonable result, because of the ratio between the number of entities simulated and the capacity of the model. However when scaling up to larger layouts this creates local buffers that prevent congestion from occurring in preceding parts of the network. To address this a finite capacity decision node should be developed, while simply limiting the capacity will introduce dead-lock situations and thus requires a more advanced solution. An example of these deadlock situations is when entities are entering and leaving a functional subsystem, they will pass through the same decision node. When this decision node has a limited capacity it might get full and prevent people from leaving the functional system, or passing through the decision node at all.

The third point has to do with the methodology. The current focus has been on developing the technical implementation of the model. Nonetheless for a complete and effective solution to this design problem not only a tool, but also the accompanying methodology needs to be developed. The current version limits it to the application of the tool, but misses the actual creation and exploration of the layouts as well as the required feedback loops.

Lastly, by focussing future work on improving the model definition and process evaluation, better insights regarding process interactions may be investigated. When properly implementing the finite capacity network, interactions between processes due to capacity limitation in the system will become more noticeable. This will also have its effect on the distributions of the results and enable more analysis there.

Combined, these developments should ensure the method is applicable to early stage design and more practical applications. This would then enable a naval architect to study the interaction between layout development and operational processes. This ought to lead to an understanding of these interactions beyond those relatively simple examples reported in this paper.

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