Winning at sea

Developing a method to provide insight in early stage naval fleet design requirements.

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TU Delft

Abstract

This thesis research focusses on winning at sea. "Winning at sea" requires presence of relevant capability at the right time and for the required time. A winning fleet is a fleet that has the capability to achieve this. The goal of this research is to define a winning fleet and to create a method that can provide insight in how such a fleet can be obtained and maintained. One of the main challenges when operating a naval fleet is to match the fleet capabilities with the capabilities required from the missions that occur over time. The first part of this problem lies in the fact that it is never known what the future will bring. Especially when looking at a period of 30 years which is the general lifetime of a naval vessel. In practice this is partly countered by introducing a major update at the halfway point in the ship's life cycle. The other part of the problem is that the fleet capabilities need to be distributed over the different vessels and vessel types. Because having an infinite fleet size would be far too expensive, certain compromises need to made. The main of which is that having a finite fleet will result in lower costs but also means that when a vessel is occupied all capabilities of that specific vessel are unavailable for other activities. For this reason it is important that the fleet composition is constructed in such a way that at all times, or at least within an acceptable error, the requirements set by the missions can be met.

The method that is created during this research acts like a proof of concept of whether such a method could be useful in the future. This research should be able to help with the iterative process of balancing the operational need and design requirements with the feasibility and affordability that occurs within the early design stages of naval fleet design. The main stakeholders in this process are Commando Zeestrijdkrachten (CZSK), the department of planning (DPLAN), and the Defence Materiel Organisation (DMO). These three parties can respectively be categorized as the user, military planner, and the supplier.

In order to reach the research goal a model has been created that simulates naval fleet behaviour. This Fleet Behaviour Model (FBM) describes a fleet as a collection of capabilities which are distributed over different vessel types. In order for this fleet to be operational it needs to comply with certain Life Support Activities (LSA) such as maintenance and the training of the crews. The operational need of this fleet is simulated by generating mission scenarios which require certain capabilities from this fleet for a specific time and at a specific location. Next to requiring mission specific capabilities from the fleet the missions also have the possibility of enemy presence. When this happens naval combat is simulated which introduces attrition into the model. The inclusion of attrition into a fleet behaviour model is what makes this research unique. Using this model the performance of multiple fleets can be tested against one or more scenarios.

After the Fleet Behaviour Model was finished and tested a Genetic Algorithm (GA) has been constructed in order to systematically find an optimal solution. In this case an "optimal solution" is the fleet of which the capabilities and the distribution of these capabilities best fit a given mission scenario. It also takes into account the difference in design priorities that can change over time. One or more of three performance parameters: mission successfulness, attrition, and fleet size can be prioritized. Depending on factors like risk and budget these priorities can change which in turn can have a drastic impact on the resulting fleet compositions.

In order to test the models' capability to provide insight into what makes an effective fleet, three test cases have been constructed. These test cases test the model on how well it can generate performance optimized fleet compositions as well as testing the performance of one fleet against a range of different scenarios. After these simulations the resulting data has been analysed in an attempt to find clues on what makes one fleet perform better than another. This insight was than translated to the broader spectrum of general early stage naval fleet design.

In conclusion, the data gathered from the test cases has proven that the model is capable of providing insight into the early stage design requirements of naval fleet design. As a proof of concept this Fleet Behaviour Model seems promising as a useful tool for naval fleet design in the near future.

Contents

Glossary

This glossary is included in order to make this document easier to read. Recurring concepts are defined here according to NATO definition. Some definitions do not exist in the NATO specification or are not specific enough so they are specified here to prevent confusion.

Term		Definition	Source
RNN	:	Royal Netherlands Navy	[-]
Mission	:	A clear, concise statement of the task of the command and its purpose.	[NATO]
Operation	:	A sequence of coordinated actions with a defined purpose.	[NATO]
Scenario	:	A knowledge representation that uses predetermined sequences of events to determine the results of interactions between known entities.	[NATO]
Capability	:	The ability of an item to meet a service demand of given quantitative characteristics under given internal conditions.	[NATO]
Capability requirement	:	A quantitative and/or qualitative description in the areas of doctrine, organization, training, materiel, leadership development, personnel, facilities, and interoperability that defines essential components and desired outcomes of a capability.	[NATO]
FBM	:	Fleet Behaviour Model	[-]
LSA	:	Life support activities. For example: maintenance and training.	[-]

1 Introduction

Winning at sea requires presence of relevant capability at the right time and for the required time. In a collaboration between the Delft University of Technology and the Defence Materiel Organisation (DMO) a research project has been constructed in order to find what makes a winning fleet. This research focusses firstly on a few main aspects such as the combined set of capabilities that is present in the fleet and the main activities that a fleet performs. The goal of this research is to develop a method that provides insight in early stage fleet design requirements. Within the time constraint it is impossible to find a definitive answer to what makes a winning fleet, therefore the result of this research will be a proof of concept regarding the usefulness of such a method.

In this introduction the general outline of the research will be discussed. First in section 1 the background of the problem will be discussed. Next, in section 2, all aspects that are included in the problem statement are introduced. Section 3 will then elaborate on the relevance of this research. This section will introduce the stakeholders and why this research is relevant to them. Lastly, section 4 discusses the research goal.

1. Problem background

When using the fleet of the Royal Netherlands Navy as an example, there are three main stakeholders in maintaining this fleet. These stakeholders can be categorized as the user(s), military planning, and the supplier. Here the user is the navy, Commando Zeestrijdkrachten (CZSK). This category is represented by the people who actually use and sail the vessels. Next, the military planning category is broadly named "Staff" and consists of different departments which have responsibilities that range from the acquisition of new equipment to maintaining this equipment. Where the equipment can mean a specific piece of equipment like a radar but can also mean an entire vessel. One of the departments is of special relevance for this research, this is the department of planning (DPLAN). This department has the responsibility of deciding what new equipment should be acquired, this includes the acquisition of new vessels for the fleet. Lastly, the supplier category is represented by the Defence Materiel Organisation (DMO). When the need for a new vessel arises it is the responsibility of DMO to come with a solution that fits the requirements set by DPLAN. DMO is in charge of the design and building of the new vessels but will often share the workload with subcontractors like a yard. These relations between the different stakeholders is also depicted in Figure 1.1.

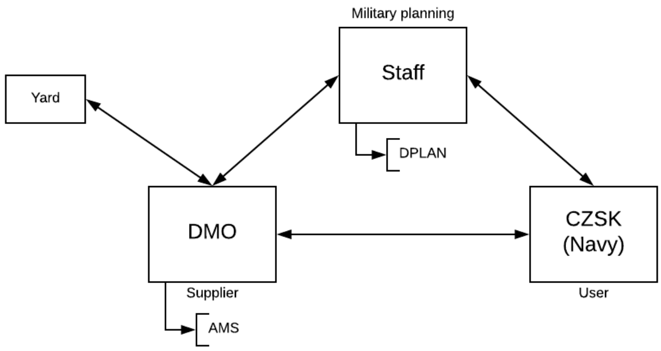


Figure 1.1: Relations between stakeholders.

When it comes to setting up the requirements of a new vessel the discussions involved mainly take place between CZSK and DPLAN. In these discussions the operational need is distilled down to basic design requirements for the new vessel in a way that it fits within the already existing fleet. These basic requirements come in the form of what the vessel needs to do, to what extent, and a budget. This information is then passed on to DMO in order to design the vessel. During the design phase DMO is frequently in contact with DPLAN. This flow of information is depicted in Figure 1.2.

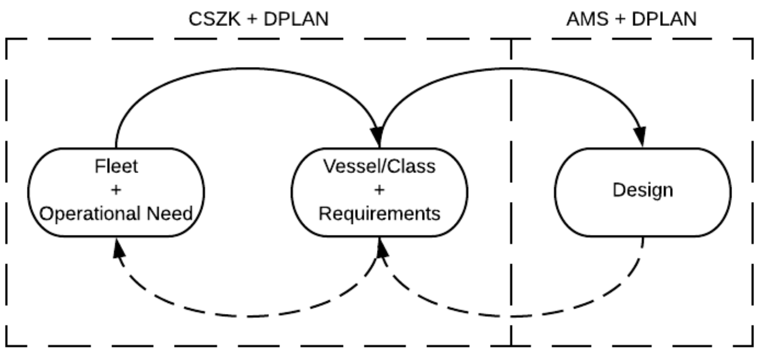


Figure 1.2: Information flow in design cycle Royal Netherlands Navy.

In reality there will always be some contradiction within the original design requirements in the early design phase. Meaning that usually the requirements that are set can not fit within the budget. Therefore compromises are needed the keep the cost down. The challenge is then to make sure that these compromises do not interfere with the operational need of the vessel. In other words, it is highly important that the changes in vessel requirements that are made in the early design phase do not result in a vessel that does not work within the fleet. this is a slow and iterative process that requires a lot of communication between all stakeholders, namely: CZSK, DPLAN, and DMO. This communication is also represented in Figure 1.2 with the dotted lines. This current method of checking whether a compromised design still meets the operational need of the fleet tends to be slow and costly. This is where the need for this research originated.

2. Problem statement

This section discusses the different aspects that come with solving this problem. The best place to start is with the operational need of a fleet. This regards the reason why you need a fleet and what a fleet should be able to do. The operational need of any naval fleet consists of a number of different activities. These activities are shown in table 1.1 as specified by NATO in the ATP 3.1 document [9]. For this research these different activities all fall under the same category named missions. Besides having a specific mission type, all missions have a few common factors. Namely, all missions have a location, a starting date and a duration.

Table 1.1: Maritime activities in the application of military power [9].

Warfare and Combat	**Maritime Security**	**Security Cooperation**
Sea Control	Support Maritime Situational Awareness	Training and Exercises
Sea Denial	Uphold Freedom of Navigation	Forward presence
Power Projection	Conduct Maritime Interdiction	Security Sector Reform
	Fight Proliferation of Weapons of Mass Destruction	Stabilisation and Reconstruction
via	Protect Critical Infrastructure	Humanitarian Assistance and Disaster Relief Operations
	Support Maritime Counterterrorism	Non-Combatant Evacuation Operations
Anti-Submarine Warfare	Contribute to Maritime Security Capacity Building	Civil-Military Cooperation
Anti-Air Warfare		
Anti-Surface Warfare		
Naval Mine Warfare		
Electronic and Acoustic Warfare		
Strike Warfare		
Amphibious Warfare		
Special Operations		
Riverine Operations		

What makes these mission types differ from each other comes down to the difference in capabilities that are required in order to execute them. For instance, where an anti-piracy mission requires some of your offensively capable vessels to be present in an area, a humanitarian mission will require your fleet to offer resources at a specific location. Also, an anti-piracy mission tends to have a pre-specified duration of a few months whereas a humanitarian mission has a more flexible duration which depends on aspects like the location and the specifics of the situation.

One of the main challenges when operating a naval fleet is to match the fleet capabilities with the capabilities required from the missions that occur over time. The first part of this problem lies in the fact that it is never known what the future will bring. Especially when looking at a period of 30 years which is the general lifetime of a naval vessel. In practise this is partly countered by introducing a major update at the halfway point in ship's life cycle. The other part of the problem is that the fleet capabilities need to be distributed over the different vessels and vessel types. Because having an infinite fleet size would be far too expensive, certain compromises need to made. The main of which is that having a finite fleet will result in lower costs but also means that when a vessel is occupied all capabilities of that specific vessel are unavailable for other activities. For this reason it is important that the fleet composition is constructed in such a way that at all times, or at least within an acceptable error, the requirements set by the missions can be met.

The last aspect to be discussed regarding the operational need of a naval fleet is the possibility of encountering enemy fleets resulting in naval combat. Including naval combat in the fleet design process introduces the possibility of attrition. This means that vessels can be lost and when this happens the capabilities of this vessel will no longer be available until the vessel is replaced. Loosing these capabilities puts a strain on the rest of the fleet because now the responsibility of the lost vessel falls on the remaining vessels. History shows that this strain can be significant enough where the remaining fleet buckles under the added pressure. Because of this the choice was made to include attrition in this research.

In order to be able to meet the operational need as described above, additional life support activities (LSA) are needed. The first of which is the maintenance of the fleet. Each vessel needs to be maintained in order to stay operational. This maintenance schedule is similar for all different vessel types and contains three different types of maintenance. These maintenance types differ in size and therefore also in duration and frequency. The different maintenance types as defined within the RNN are IP, OB, and the daily maintenance. The first maintenance type is called the "IP", which literally translates to "Conservation Project". This is the largest and most impactful type of maintenance and is used to upgrade the vessel with the new technologies that have been created and tested since the vessel was originally designed. This type of maintenance occurs at the halfway point in a ship's life cycle and therefore has a frequency of 15 years. Generally this maintenance takes up to two and a half years. The next type of maintenance is called the "BO", which translates to "Appointed Maintenance". This type of maintenance is intended to keep the ship operational and efficient. During the BO the vessel goes into dock once every 3 years. This maintenance takes around 6 months at a time. Lastly, there is the daily maintenance. This maintenance handles the everyday repairs that are needed to keep the vessel operational. This maintenance tends to be scattered over the year but when summed up comes down to about 3 months of maintenance each year.

The next LSA needed to be able to meet the operational need is the training of the crews. A fleet can never be effective when there is no one to operate the individual vessels in an effective manner. Just as maintenance this takes up a significant portion of the ship's life time. Again, this is time that the vessel is unavailable for executing the missions for which it is intended.

In the end a fleet is operational when the capabilities required by the missions over time can be met by the fleet capabilities while maintaining the LSA. The biggest constraint in reality in this balance is the budget that is available. However, an operational fleet is not necessarily an effective fleet. Furthermore, the most effective fleet depends on the situation, and will therefore change when the situation changes. For example, during a time of peace the most effective fleet will most likely be entirely different from a wartime oriented fleet. Next to being situationally dependent the effectiveness also depends on certain preferences set when designing the fleet. For example a fleet can be completely designed with the focus on mission successfulness will differ from a fleet designed to be cost-effective. The combination of these trade-offs is where the challenge of this research lies. To create a method that is able to test the effectiveness of an operational fleet and find what makes the most effective fleet given the time and budget constraints while keeping the fleet design philosophy in mind.

3. Relevance

The method that results from this research can be relevant to more than one of the previously introduced stakeholders. Firstly to the the department of planning. It is the responsibility of DPLAN to decide what is needed in the Royal Netherlands Navy. Right now these decisions are made based on a combination of experience, future prospects, and budget. Providing a method that is able to test the effectiveness of a fleet by running it through multiple different future scenarios can help with the "why" part of this problem. More specific, it can help with why you want a specific vessel or capability over another. A fitting example situation that is happening now is the replacement of the "Walrus" class submarines. A trade-off question that needs to be made here is that the budget allows for a couple large new submarines or more smaller submarines. Being able to test which of these two options is the best choice from a fleet design perspective, or whether it is better to replace these capabilities by an entirely different vessel type, can help to speed up the decision making process. A method to help with these trade-off questions does not yet exist at the moment of writing this.

Another relevant use case for such a method lies in the early design phase handled by DMO. With the ability to test fleet effectiveness comes the possibility to test the usefulness of new vessel types. Instead of speeding up existing discussions this could spark new discussions which can lead to new effective fleet compositions.

Lastly, this results from this research could be used to provide insight into how to improve certain protocols that influence the fleet behaviour and therefore the fleet effectiveness. For example how a more flexible vessel maintenance protocol which allows for pre-emptive rescheduling could lead to a change in the performance of a fleet. Similarly the same could be tested for the training schedule of the crew.

4. Research goal

With a better understanding of the nature of the problem it is now time to better define the research goal. This research goal will state what the results of this research project aims to deliver.

The problem statement, section 1.2, stated that in order to have an operational fleet at least four aspects need to be balanced.

1. Required mission capabilities
2. Fleet capabilities
3. Life support activities such as training and maintenance
4. Budget

First, the fleet capabilities need to be matched with the capabilities that will be required by the missions that occur over a specified period of time. This specified period of time is the time over which a reasonable estimation can be made of the type of situations that will be encountered. These fleet capabilities also need to be distributed over the different vessel types that already exist within the navy. The execution of the missions needs to be done while also maintaining the existing fleet and training the crew members. Lastly, all of this needs to fit within the available budget.

Given these constraints of an operational fleet the goal of this research is to develop a method that can provide insight into what makes a fleet effective, or "win at sea". Since the effectiveness depends what you want to do with your fleet, the fleet prioritization, the answer to whether a fleet is effective is subjective to change. The fleet prioritization can be boiled down to three main aspects that can individually be prioritized. These aspects are:

- *Mission successfulness.* This is the priority of successful execution of as many missions as possible over the specified time frame.
- *Fleet durability.* This aspect prioritizes the lack of damage and losses sustained in the vessels throughout their life cycle.
- *Cost-effectiveness.* When designing a fleet with cost-effectiveness in mind the goal is to have an effective fleet for lowest overall cost. This includes both the initial investment cost and the cost throughout the life cycle of a vessel.

The end result needs to take the fleet prioritization into account when evaluating the effectiveness of a fleet.

Lastly, it should be noted that the goal is not to provide a definitive answer to what makes a fleet effective. Due to the combination of the large scope that comes with the behaviour and performance of a naval fleet and the time constraint of a master thesis, the research will not go into high detail on any specific aspect but will instead touch upon a wide variety of aspects with a surface level of detail. Therefore the resulting method should be considered to be a proof on concept instead of a finished product capable of providing trustworthy conclusions. At the end of this research it should be clear whether a simple method that combines a limited selection of aspects of naval fleet behaviour is capable of providing useful insight in naval fleet design in the future.

2
Method

This chapter will elaborate on the method that is used in order to reach the research goal. First section 1 will discuss the requirements of the method in order to come to an answer. After which section 2 will take a look into the already existing work on this subject. This will show the pieces that still need to be filled in. Next, after the decision is made to create a model, section 3 will elaborate on how the different aspects regarding naval fleet behaviour need to be implemented. Then section 4 discusses the need and implementation of the verification and validation of the fleet behaviour model. Lastly, section 5 describes how the model is tested using three different test cases.

1. Requirements

In Chapter 1, the introduction, the problem statement and research goal have been described. Using that information the requirements and restrictions of the to be developed method can be outlined. This is done by starting at the goal and then work top-down to see what is needed at every single step.

Firstly, in order to get insight into what makes an effective fleet there is a need to be able to test the performance of a fleet. This can be done by constructing performance indicators that test the fleet on aspects that align with the operational need. Next, in order to test the performance of a fleet you need to know how a fleet behaves and fares throughout different scenarios. To be able to do that it important to know the operational need of the fleet and how to meet this need. The operational need of a fleet, for this research, is restricted to being able to execute missions with the possibility of attrition. From this follows the need of a collection of capabilities that is available to meet the operational need. These capabilities then need to be distributed over a number of different vessel types. Lastly, the fleet that results from the sum of these vessels needs to be maintained and the crew needs to be trained. Since these life support activities take up a significant portion of the ship's life cycle they need to be included in the requirements.

The requirements for a method that can provide insight in early stage fleet design are summarized below ordered from the goal down to the subsequent requirements.

6. Evaluate performance of fleet.
5. Simulate fleet behaviour.
4. Simulate operational need including:
    (a) mission representation,
    (b) capability matching,
    (c) mission execution,
    (d) attrition.
3. Simulate collection of available capabilities.
2. Distribute capabilities over vessel types.
1. Construct virtual fleet, including fleet conservation related activities:

(a) maintenance,

(b) training.

From these requirements the conclusion is made that there is a need to build a model that describes the fleet behaviour. This Fleet Behaviour Model (FBM) should be able to simulate the behaviour of any fleet composition in different scenarios. This also requires that next to the fleet and vessel capabilities, processes such as maintenance, training, and attrition are included.

2. Literature

When designing a product it is important to first have a clear idea on what it is that you want this product to do and to what extend. Otherwise you may end up with something that costs a lot of money but is of little use when trying to solve the original problem. This is no different when looking at naval fleet design. In the case of a naval fleet it is important to first know the operational need of the fleet in order to come to the early stage design requirements. The challenge that navies constantly encounter in this regard is the fact that the future is volatile and therefore hard to predict. When working with vessels that have a life cycle of around 30 years this becomes a problem. The generalized approach that countries take to solve this problem is discussed by Stuart E. Johnson and Arthur K. Cebrowski in an article title *Alternative Fleet Architecture Design*, [14]. As the title suggests elaborating on the current method of defining the operational need of a naval fleet is not the main goal of this article. Instead, the authors discuss the viability of an alternate fleet architecture design. However in order to do that they go into detail on the process of defining the fleet capability requirements. This process is depicted in Figure 2.1.

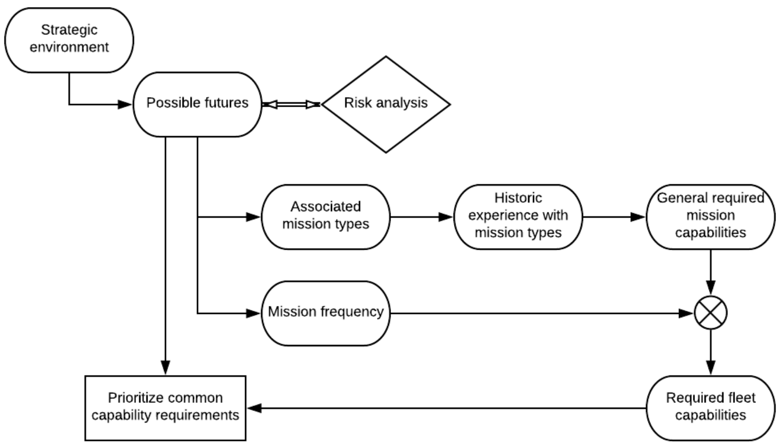


Figure 2.1: Process of obtaining fleet capability requirements.

Going through the flow chart depicted in Figure 2.1 the process of defining the required fleet capabilities starts with analysing the strategic environment. This is the current state of the world with all the participants. The participants can range from countries to specific terrorist organisations which are individually specified as allies or (potential) enemies. The nature of the future threats is likely to be characterized by complexity. The threats coming from terrorist, regional powers, or rogue states in the future would all pose a wide variety of enemy capabilities including mines, quiet submarines, shore-based missiles, and numerous small craft. Within this mix of potential threats the next step is to come up with as many potential future situations as possible. All these different possibilities will then undergo a risk analysis where the possibility of occurrence and the potential consequences are weighed. The future statements that pose the highest risk are then analysed on the missions that they would impose on the naval fleet. So what type of missions would occur in this scenario and with which frequency? After comparing the prospected mission types with historic experiences a conclusion can be made on what capabilities will be required when encountering these missions. Some examples of capabilities that can be required by specific mission types are anti-surface, anti-air, anti-submarine warfare, nuclear deterrence, response time, and humanitarian relief. Combining these required mission capabilities with the mission frequency will give an indication of what your fleet needs to be capable of.

The required fleet capabilities can vary greatly between different future prospects. Johnson and Cebrowski list three ways to approach this problem.

- Plan for one future, hedge for the others.
- Prepare for all futures with separate fleets.
- Plan for all futures by prioritizing the common required capabilities.

In reality the most common approach is to plan for all futures by prioritizing the common capabilities. The reason is because this is the most economic approach. Capabilities required especially for one future but not for the other could be kept more modest, in scale or sophistication. Because of this, setting priorities and assessing risks becomes critical. The core required capabilities common across the different future prospects receive priority over other capabilities. However, it would be a mistake to assume that the different requirements of the different prospects cannot be met at all. Any fleet/capability composition that tests well against all future prospects should be favoured over compositions that fare better against just one.

Following the process of defining the required fleet capabilities comes the process of modelling the behaviour of such a fleet. Similar studies into naval fleet behaviour have been done in the past. Seth Bonder [1] lists some great examples of historic models, perspectives and implementations. However, none of the recent existing models have tried to incorporate the attrition of ships in to the general fleet behaviour. Of course there are tons of models which describe the processes of transit [3], combat [6], maintenance [7], and resupplying [15] individually. These models have been used as a reference while working on this thesis and will be discussed shortly here.

Modelling the behaviour of a fleet, naval or not, is not anything new. Whether a fleet of vessels, truck, planes, or trains are discussed, the models to simulate their behaviour are all quite similar. The method that is often used in simulating these multi-agent systems is discrete-event simulation. This method lends itself particularly well for systems where multiple intelligent entities combined have to fulfil a main task and/or goal. However, one of the major differences between the transport industry and the military is the possibility of combat. By implementing combat into this Fleet Behaviour Model it is possible to take attrition, the loss of vessels, into account when designing a fleet. Implementing attrition into this model is what makes this model different from other naval fleet behaviour models. Therefore, it is important to look into the different approaches that can be used in order to implement attrition.

To simulate combat situations between one or multiple naval vessels there is a wide range of models and methods already available. These models range simplicity, transparency and complexity. On one end of this spectrum there are models like Hughes' salvo model [6]. This model consists of a set of simple equations which is designed to capture some of the important dynamics of modern naval combat. In short, this model simulates the exchange of missile salvo's between two forces (A and B). This incorporates the number of missiles launches, missiles that will hit without a defence, deflected/destroyed missiles and the number of hits a single vessel can take. This model shines in its simplicity but therefore also leaves out many factors that might be of importance during an actual battle. Factors like the ocean's surface, weather conditions and operator alertness are not taken into account. Advanced tactics are not impossible to implement but this will require some creativity from the user. The advantages and disadvantages of a simple model like Hughes' Salvo Model are well summarized in *When is model complexity too much? Illustrating the benefits of simple model with Hughes' Salvo equations.* by John E. McGunnicle and Thomas W. Lucas [16].

On the other side of the spectrum we can find models such as complex Joint Warfighting System (JWARS). JWARS is a campaign-level model of military operations developed by the Office of Defence (OSD) in the United States [8]. It puts a special emphasis on the Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR) processes. It includes an explicit three dimensional battlespace, the effect of terrain and weather, logistically constrained force performance, explicit representation of key informations flows and perception-based command and control. These features show how comprehensive this model is and as expected is this both its strength and weakness. Since JWARS tries to implement so many new modelling concepts it becomes tremendously complex. To operate it comes with a very steep learning curve and it will take a lot of practice from the user to be used efficiently.

In *Military modelling for decision making* [5], Hughes describes that the choice between these two types of models comes down to whether the factors that are left out in the simple model will actually make a big difference in the answer that you are looking for. If the answer to this is yes then the simpler the model the better. This is because of the earlier mentioned fact that a simpler model also brings a lot of transparency to the answer. To accompany this motivation to choose for a simpler and more transparent model, in *A proposed foundation for a theory of combat* [4] Clint Ancker says: "The most successful procedure for model building has been to work from simple and small to the larger and more complex".

An example that springs to mind here comes from a similar model that was build for the Royal Canadian Navy. They made a model that simulated fleet behaviour, mainly focussed on resupplying methods and stationing. In the end the model is never used just because the model acted like a black box. In other words nobody was able to fully explain what steps were made for one specific answer to come out and therefore the answers were not to be trusted.

Lastly, the use of game theory [11] for simulating naval confrontation has briefly been considered. While this could be a very suitable and behaviour approach it has not been used because options like Hughes' Salvo Model are already available and discussed. Making an entire new naval combat model from scratch falls outside the scope of this thesis.

3. Model

With the requirements as shown in section 1, after which section 2 elaborated on the existing work in this area, this section will show the outline of the final Fleet Behaviour Model.

The first aspects that needs to be looked into is the method of generating events/missions over time and the set of capabilities, in the form of a fleet, on the other side to match and execute those missions. As stated in Chapter 1, it is not viable to incorporate every single detail that comes with this highly complex system of capability matching. Therefore the missions requirements and fleet capabilities need to be simplified. In order to do this a selection of 5 main capabilities is made: Landing, Anti-Air Warfare (AAW), Anti-Surface Warfare (ASuW), Anti-Submarine Warfare (ASW), and Supply. These are capabilities that can be present at a single vessel and the combination of these capabilities on one vessel defines the vessel type. A total of 7 vessel types are defined by this distribution of capabilities. These types are: Submarines, Landing Platform Dock (LPD), Luchtverdedigings- en Commandofregat (LCF), Multi-purpose frigates, Patrol vessels, Join Support Ship (JSS), and Combat Support Ship (CSS). The distribution of capabilities across these vessels is shown in table 2.1. It needs to be noted that this is a very basic approximation, the point is that different vessel types can be implemented and the fleet capabilities is the sum of the individual vessel capabilities.

Table 2.1: Vessel type capability matrix (approximation)

	Landing	AAW	ASuW	ASW	Supply
Submarine			X		
LPD	X				
LCF		X			
M-Frigate		X	X	X	
Patrol			X		
JSS	X				X
CSS					X

By implementing different vessel types with a different set of capabilities it becomes possible to give a representation of the total fleet capabilities. This is the sum of all capabilities within the fleet composition.

By implementing the vessel capabilities in this way it is now possible to have capability requirements in the to be generated missions. This can be done by picking a number of random capabilities as a requirement for the fleet in order to be able to execute that particular mission. The selected vessel for that mission combined to have the required capabilities available. Chapter 3 will go into more detail on how this selection process works.

Next to the required capabilities the missions also need a location. In order to implement this five locations in and around Europe have been selected as possible mission locations. These locations are: Libya, Syria, Malta, Estonia, and Germany. Moving between these locations is represented using a distance matrix.

The sixth location is Den Helder which is used as the main home base for the fleet. Additionally the missions can have a required "time on location". This means that the vessels need are given a minimal duration for which they need to present at the mission location.

To be able to comply with this mission representation the individual vessels also need some additional information. Firstly, all generated vessels need a cruising speed. Since the weather will not be taken into account during this research the combination of the previously mentioned distance matrix, the cruising speed, and the vessel location will be the only factors in determining the time of arrival. The next vessel specific parameters that need to be specified are the maintenance and training schedules. Modelling the maintenance and training process in full detail would go beyond the goal of this research. However it is important that vessels are regularly working on these tasks and are therefore not available to be selected for a mission elsewhere. Therefore these processes will be modelled as such and will only affect the availability and location of the individual vessels. The last vessel specific parameters regard the offensive capabilities. From the literature study the decision is made to go with the Hughes' salvo model in order to implement the effects of attrition into the Fleet Behaviour Model. Therefore the vessels offensive capabilities need to be represented in a way that complies with this model. The parameters that need to be specified are: striking power, defensive power, staying power, scouting effectiveness, the defensive alertness, and the ammunition storage. These parameters will be further explained in Chapter 3. Of course any battle at sea always consists of at least two parties so these same parameters also have to be specified for the enemy fleets.

With now a method of simulating missions and a fleet there is also a need to find a way of selecting the best suitable vessels each time a mission occurs. This selection process is dependant on multiple key parameters such as vessel availability, maintenance and training schedules, transit times, and the possibility of a battle and if so of what scale. Because of the increased complexity that each of these parameters bring to the table the modelling of this selection process needs to be elaborate. Therefore a lot of time is put into defining this within the confines of the Fleet Behaviour Model of which the result is also explained in Chapter 3.

When all these aspects are combined into one Fleet Behaviour Model it becomes possible to simulate the behaviour of any fleet against a wide range of scenarios. As stated previously meeting all these aspects makes sure that a fleet is operational but not necessarily effective. In order to find what makes an effective fleet first one needs to be found. This can be done using the FBM by systematically varying the input parameters such as the fleet composition and mission scenarios and then check the performance and comparing the different fleets. However doing this by hand would take up too much time. Therefore an algorithm is made to automatically vary the input parameters and evaluate the fleet performances. The specific type of algorithm that is used is a genetic algorithm of which the justification and implementation can be found in Chapter 4.

4. Verification & validation

According to the international standard in Systems and software engineering — System life cycle processes [10], verification and validation are defined as:
verification:
confirmation, through the provision of objective evidence, that specified requirements have been fulfilled.

Note 1 to entry: Verification is a set of activities that compares a system or system element against the required characteristics. This includes, but is not limited to, specified requirements, design description and the system itself. The system was built right.

validation:
confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled.

Note 1 to entry: A system is able to accomplish its intended use, goals and objectives (i.e., meet stakeholder requirements) in the intended operational environment. The right system was built.

Verification and validation are key words when it comes to any scientific research. Without this it is hard to say whether the results can be trusted. As stated above verification is the process of checking whether the calculation are done correctly where validation checks whether the correct calculations have been done. In other words, verification checks if the solution is correct within the boundary conditions that are set. Validation in turn checks if the solution still represents reality within the expectations or with an acceptable error.

Validation can be done by comparing the results from either building a prototype or full-scale tests and comparing them with the model results. However, building thousands of different fleet compositions and let them run through different staged scenario is not reasonably achievable. Therefore the resulting Fleet Behaviour Model will not be validated for this research.

The model is verified however. This is done by going through the simulation step by step while checking at every interval if the model works as intended. The full verification process of the Fleet Behaviour Model is described in Section 3.7.

5. Testing

After the Fleet Behaviour Model is verified and an algorithm is constructed to find an optimal solution it is time to test the full model on its capability to provide insight in early stage naval fleet design. In order to test this a set of three test cases are constructed.

1. Find an optimum fleet composition for a given set of scenarios. This should give insight into the kind of fleet capabilities to strive for in the long term.
2. Given the example situation where a budget is available to invest in new vessels, lets say submarines. From this budget it is possible to buy a couple large submarines or more smaller ones. The finished model should be able to give insight into which of the two option is better from a fleet effectiveness perspective.
3. The finished model should be able to test one specific fleet against a wide range of scenarios. This should give a handle on the versatility of that specific fleet.

The results of these test cases will be analysed in Chapter 5. This chapter will go into detail on what design parameters make a naval fleet effective.

3
Fleet behaviour model

To be able to find a fleet that is able to win at sea first one needs to know what task a naval fleet successfully needs to do before being able to operate. To accomplish this a fleet behaviour model is made. This model is designed to be able to generate lots of different vessel combinations and missions while also taking into account the supporting tasks a fleet needs to do.

Looking at these requirements for the model, the chosen simulation method is discrete event simulation. This method models the system as a discrete sequence of events in time. Each event occurs at a specific instant in time and only these events can change the state of the system. Between these events the system is assumed to not change. Discrete event simulation is common in military models, some good examples can be found in *Applications of discrete event simulation modelling to military problems* by R.R. Hill, J.O. Miller and G.A. McIntyre [13].

Figure 3.1 visualizes the idea with which the model is created. The input for this model are a fleet composition and a set of mission scenarios. These mission scenarios are a set of missions that pop-up at specific moments during the simulation time. Next, the Fleet Behaviour model simulates how that specific fleet would behave in that given set of scenarios. This model incorporates multiple processes such as: mission analysation, vessel selection, mission execution and maintenance. Lastly, when the full simulation is done, different performance parameters are given as an output. The performance parameters can contain information such as: how many missions have been executed successfully, which missions failed and why or how the maintenance schedule needed to be adjusted. These performance parameters can than later be used to grade that particular fleet.

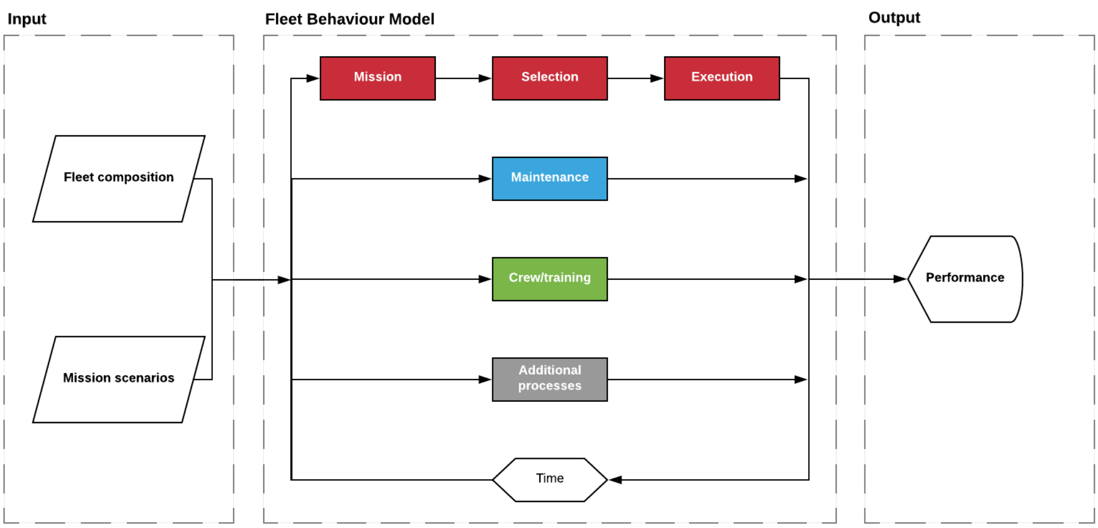


Figure 3.1: Model layout description.

The main purpose of a naval fleet is to be present at sea. This means that if something happens in the world, whether it is a humanitarian mission or war, vessels need to be able and available to act. This objective is depicted in the "Mission, Selection, Execution" line. This represents every situation that requires the need of a naval fleet. Of course, to be able to execute these missions there are supporting tasks that need to be done. For example: vessels need to be maintained, supplied, and the crews need to be trained. In this model these supporting tasks are viewed as having an influence on the availability of each vessel and therefore on the ability of the fleet to execute missions at sea.

This chapter will elaborate on the inner workings, assumptions, and limitations of this fleet behaviour model. Section 1 explains how the fleet is generated, sections 2 - 4 will elaborate on the previously mentioned main objective line of "Mission, Selection, Execution" and section 5 will show how the maintenance of the fleet is being modelled. Lastly, section 6 will explain how opposing fleets are taken into account.

1. Fleet

The fleet that is used through the simulation is generated in the initialization part of the model. The fleet consists of n vessels of which m different vessel types. The vessel types are defined by assigning specific capabilities to each vessel. To explain this further table 3.1 shows an example capability matrix.

Table 3.1: Vessel type capability matrix

	Landing	AAW	ASuW	ASW	Supply
Submarine			X		
LPD	X				
LCF		X			
M-Frigate		X	X	X	
Patrol			X		
JSS	X				X
CSS					X

As shown in table 3.1, the capabilities that can be assigned to vessels are: Landing, Anti-Air Warfare (AAW), Anti-Surface Warfare (ASuW), Anti-Submarine Warfare (ASW), and Supply. Of course this can easily be expanded on in the future.

In the optimization phase of this research the size and consistency of the fleet can be dynamically changed to find search for an optimum fleet. Furthermore you could fix part of the fleet and let the model generate vessels to compliment that specific fleet for a certain scenario. It will be interesting to see if the generated vessels comply with current vessel types or that new vessel types would be something to look into.

Besides the capabilities each vessel is given a initial location, speed, and salvo model parameters. The salvo model parameter are used to simulate engagement against an opposing fleet and will explained later on in this report.

2. Generating missions

In the fleet behaviour model every day has a chance for a mission to be generated. This chance is a variable parameter and can be changed according to the situation. When no mission is generated all vessels in the fleet will continue doing what they were doing and the model will jump to the next day.

When a mission is generated, it creates several parameters. These parameters are:

- Location
- Time on location
- Salvo model parameters enemy fleet
- Required capabilities

Further explanation on how these parameters are generated follows below.

Location

At the moment of writing this report there are 6 locations where vessels and/or missions can be situated. These locations are: Den Helder, Libya, Syria, Malta, Estonia and Germany.

Although this is a limited amount of locations, its is enough to give mobility to the fleet. Furthermore this can easily be expended in the future. For transit between ports a distance matrix, table 3.2, is used.

Table 3.2: Distance matrix

	Den Helder	Libya	Syria	Malta	Estonia	Germany
Den Helder	0	2600	3500	2500	1100	600
Libya	2600	0	1300	200	3700	3500
Syria	3500	1300	0	1000	4500	4100
Malta	2500	200	1000	0	3500	3300
Estonia	1100	3700	4500	3500	0	600
Germany	600	3500	4100	3300	600	0

Salvo model parameters enemy fleet

When the mission is generated it also generates the parameters which describe how strong the opposing fleet on location is expected to be. This information will later be used to simulate the confrontation. This is done using Hughes' Salvo Model [6] and will be explained further in section 3.4.

The parameters that are generated are:

- Number of vessels
- Staying power, Number of hits needed to put a vessel out of action
- Salvo size, Number of missiles that will be launched successfully per salvo
- Number of missiles that will hit if there is no defence
- Defense power, Number of shots that are destroyed or deflected per salvo
- Amount of offensive and defensive ammunition on board

Required capabilities

Missions that are generated will require certain capabilities to be able to accomplish them. Up to three capabilities are randomly picked from the available capabilities in the fleet. As shown in table 3.1, these capabilities are: Landing, AAW, ASuW, ASW and Supply.

3. Vessel selection

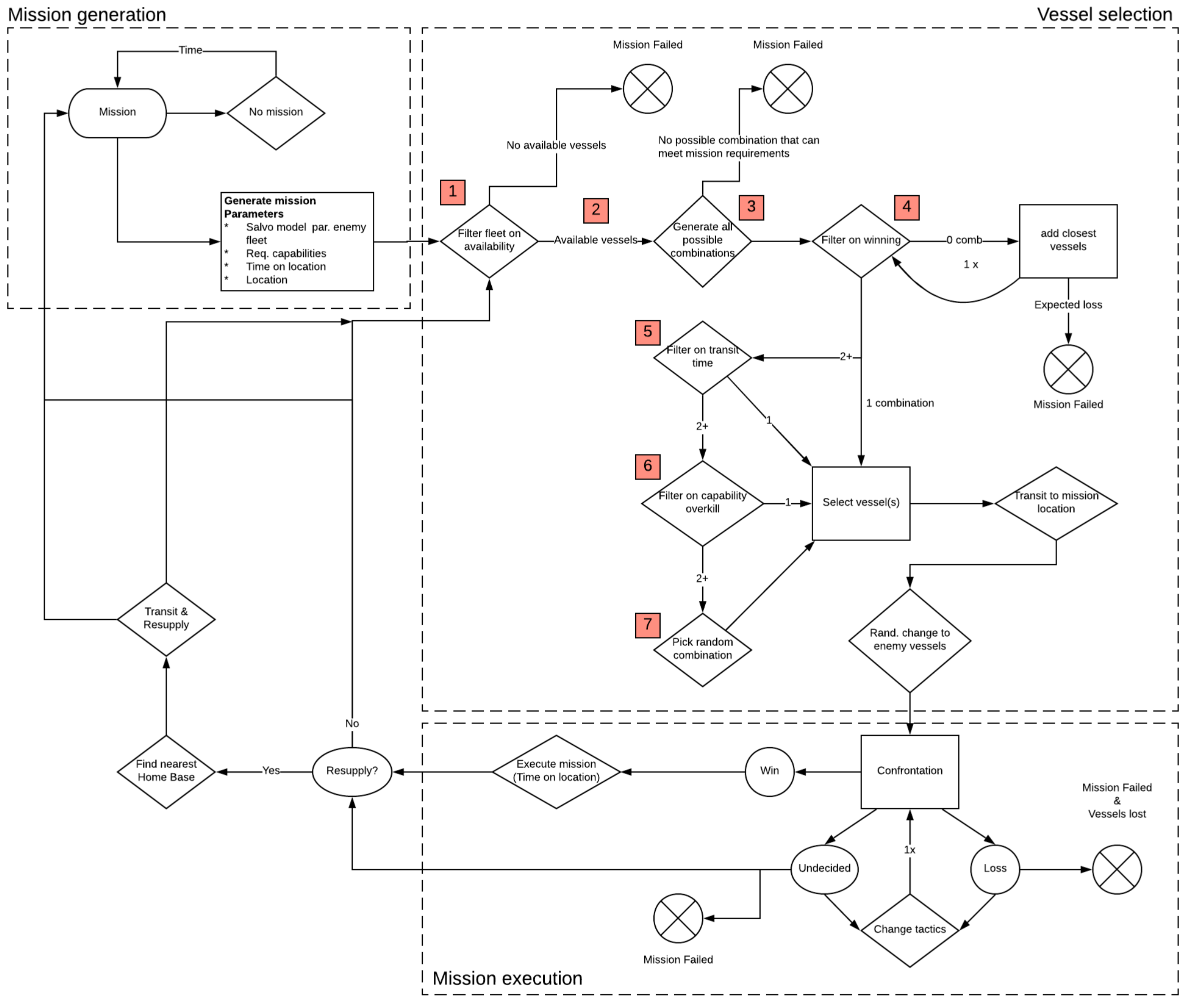


Figure 3.2: Mission simulation flow chart.

When a mission is generated the next thing to do is to select the best combination of vessels to execute this mission. This is done in a sequence of steps that is shown in Figure 3.2 but will be elaborated on below. The sequence of the actions are indicated using numbers. These numbers are also represented in Figure 3.2.

1) First an availability matrix is generated by filtering out all vessels that are unavailable at the moment the mission is generated. Vessels can be unavailable for a few different reasons. They can either be in maintenance, already working on a different mission, resupplying, or they can be destroyed in a previous mission. In this last case the vessels will be unavailable for the remainder of the simulation.

In the case that no vessels are available the mission will be considered as failed. This is because the requirements, in this case as basic as having vessels available, could not be met.

2) Next, the availability matrix is filtered on the required capabilities that are needed to execute the mission. This means that all vessels that do not have any of the required capabilities on board are removed from the list of potential vessels.

3) From this filtered list all possible combinations of vessels, that combined can meet the required capabilities of the mission, are generated. The number of different combinations that is generated can differ quit heavily.

It is possible that no possible vessel combinations can be generated. This happens when a certain capability can not be met because all vessels that have that capability are otherwise occupied. In this case the mission will be considered as failed because the requirement could not be met.

4) Next, all generated vessel combinations are filtered on their potential of overcoming the opposition on the mission location. The engagement is simulated and when the vessels are not expected to win that combination will be removed as an option. For this simulation Hughes' Salvo Model is used, this model will be further explained in section 4. This model uses the salvo model parameters that have been generated before. The parameters that describe the strength of the opposing fleet need to be viewed as intel. In other words this is the expected strength of the opposition. This filtering has 3 possible outcomes:

(a) Zero combinations can both meet the required capabilities and is expected to win. In this case there is the one time possibility to take the closest vessel to the mission location and add this vessel to the combination and rerun the engagement simulation. When this returns no results no vessels will be sent to the mission, because it will only result in loosing the vessels, and the mission is considered to be failed. In the case that the added vessel does change the expected outcome either option 2 or 3 will active.

(b) One combination can both meet the required capabilities and is expected to be able to overcome the opposition. In this case the optimal combination of vessels is found to execute the mission and thus these vessels are selected.

(c) Two or more combinations can meet the required mission capabilities and are expected to be able to overcome the opposition. In this case more filtering is needed to find the optimal combinations of vessels for this mission. The next steps will elaborate on these filtering steps.

5) In the case that two or more combinations of vessels can meet the required mission capabilities and are expected to be able to overcome the opposition on the mission location, more filtering steps are required. First the combinations are filtered on their time to arrive on location. This time is defined as the time that it takes for the last vessel to arrive. This can result in two types of outcomes:

(a) One combination can get there faster than all other possible vessel combinations. In this case this combination is selected.

(b) Two or more combinations have the same arrival time. This usually happens when the last vessel is the common factor in different possible combinations. In this case more filtering is required.

6) If in this stage there are still more than one possible combinations of vessels that can meet the required capabilities, are expected to win, and have the same arrival time one last filtering can occur. In this case the combinations are filtered on capability overkill. This means that remaining combinations are filtered on the amount of capabilities that they take out of the available fleet. This way the available fleet will be as diverse as possible and therefore have a higher chance to be able to successfully find a winning combination for future missions. Again this can result in two different outcomes:

(a) One combination uses the least amount of capabilities while still complying with the required mission capabilities. In this case this combination of vessels is selected to execute the mission.

(b) Two or more combinations use the same amount of capabilities while still complying with the required mission capabilities. In this case more filtering is needed to find the optimal combination.

7) In the case that after all this filtering there are still more than one possible vessel combinations a random combination is picked to execute the mission. In the future more filtering conditions can be applied.

4. Mission execution

After the best combination of vessels for a certain mission is selected, the vessels are sent on their way. At location the vessels first regroup, so the total transit time can be assumed to be equal to the transit time of the slowest vessel. Once at location, first the opposition, if present, needs to be taken care of before the rest of the mission can begin. This confrontation is modelled using the Hughes' Salvo Model [6]. This model uses the aforementioned salvo model parameters. These parameters are considered to be intel and can change between the moment of departure and arrival. This is done by applying a random change to the Hughes' salvo This needs to be done to ensure uncertainty of the confrontation. If this uncertainty would not be incorporated the selected vessel would never lose a confrontation, otherwise they would not have been selected in the first place.

Hughes Salvo Model

As described in the introduction Hughes' Salvo Model is a very basic model that tries to give the most likely outcome of a confrontation between two different fleets, fleet A and B. The basis for this model can be seen in equations (3.1) and (3.2).

$$\Delta B = \frac{\alpha \cdot A - b_3 \cdot B}{b_1} \tag{3.1}$$

$$\Delta A = \frac{\beta \cdot B - a_3 \cdot A}{a_1} \tag{3.2}$$

The parameters, previously referred to as the salvo model parameters, in these equations represent:

ΔA, ΔB	:	Number of vessels taken out of action after one salvo.
α, β	:	Striking power of each attacker. This is the number of missiles that will hit if there is no defence.
A, B	:	Fleet size of each attacker. This is the number of vessels that are present for both parties A and B.
a_3, b_3	:	Defensive power that each defender will destroy or deflect, when alert and ready to do so, per salvo.
a_1, b_1	:	Staying power of each defender. This is the number of hits that is needed to put a vessel out of action.

With: $\alpha = H_a \cdot a_2$,

$\beta = H_b \cdot b_2$

Where a_2 and b_2 are the number of missiles that are launched with each salvo and H_a and H_b represent the accuracy of missiles launched, or the chance that a launched missile will be on target. Therefore the product of a_2 and H_a will give the number of missiles that will be on target per salvo.

The model as described above is its most basic form but this can be expanded upon. The first additional parameters try to account for the difference in effective range between fleet A and B. The effective range has an offensive aspect, e.g. long range missiles, and a defensive aspect, e.g. sensors. The terms in question are called the *scouting effectiveness*, σ, and the *defender alertness*, δ.
The scouting term can take a value from zero to one. Zero means no information about the enemy and no ability to hit any targets. The value is also zero when targets are detected but out of missile range. A value of one is used when all targets are detected and all within range.

The defender alertness term can also take a value between zero and one. In this case a value of zero is assigned when no prior knowledge is available of an impending attack, of course this can only occur during the fist salvo.
Adding the scouting effectiveness and the defender alertness into the salvo equations yields:

$$\Delta B = \frac{\sigma_a \cdot \alpha \cdot A - \delta_b \cdot b_3 \cdot B}{b_1} \tag{3.3}$$

$$\Delta A = \frac{\sigma_b \cdot \beta \cdot B - \delta_a \cdot a_3 \cdot A}{a_1} \tag{3.4}$$

Different vessel types will have different salvo parameters. When using the salvo equations to model the confrontation and attrition of vessels this is addressed by taking the mean value of all parameters before putting them into the equations. Doing this allows for vessel diversity where one type can be more specialized for combat than others. However this will also result in a small error since losing a vessel will result in a linear decline of the fleets capabilities. In reality this is non-linear since loosing a frigate will have a drastic different result for the total offensive capabilities than loosing a patrol vessel for instance.

Lastly, the basic Hughes' Salvo Model is expanded with keeping track of the available ammunition of each vessel on both sides. This is a direct result of the uncommon situation where both fleets are equally matched. In this case all missiles in a salvo will be deflected or destroyed from both sides and the model is stuck in an infinite loop. By keeping track of both offensive and defensive ammunition this loop becomes finite. As is to be expected the salvo size is reduced when less missiles are available then the demanded salvo size.

Using Hughes' Salvo Model comes with the significant benefit of simple and transparent. Once you know the very basic equations and parameters everyone will be able to understand the outcome. The downside however to a simple model like this is that it does not consider factors that in reality could be key to making the difference between winning and loosing the battle. To name a few of these: the ocean's surface, weather conditions, and the operator alertness are not taken into account. In addition to this, the application of complex tactics and the ability to adapt to your enemies actions are not impossible but hard to implement. The current implementation does not take any of these aspects into account but all could be added in a later stage if this is deemed necessary.

Possible mission results

The confrontation as modelled by the Hughes' Salvo equation will result in one of three possible outcomes. The first outcome is that the battle is won. In this case the opposition has been overcome and the rest of the mission can be executed, for example delivering supplies. In the model this is handled using a required time on location instead of specifying and simulating the actual mission. After this time has passed the vessels will resupply if needed after which they will be available again for other missions.

The second possible outcome is losing the battle. In the case that the opposing fleet is stronger than the intel suggested the fleet can be lost. Before this happens however the fleet has one last trick up their sleeve. When facing a loss the fleet will increase their striking power and defensive power by 1. This can be done only once. This increase is to account for the safety factor when selecting the vessels for a mission, as it is never wise to select vessels at their maximum capability. If, after this last resort, the battle is still lost than the vessels will be lost for the remainder of the simulation time.

The third and final possible outcome is the case where the battle is undecided. In the case that both fleets are equally matched both salvo's will be deflected or missed and no damage will be done. To prevent the model to become stuck in an infinite loop, ammunition is taken into account. When this runs out on both sides before either side is taken out completely the battle will be considered to be undecided. In this case the model considers the mission to be failed but the vessels are not lost. The vessels will resupply and afterwards will be available again to be selected for the next mission.
In reality of course it depends on the type of mission for this result to be considered as a failure or not. An example where this mission would still be considered a success would be the scenario where the mission is to eliminate the threat of an enemy submarine. While the submarine was not destroyed in battle, she is still out of ammunition and thus is no longer a threat. However these highly specific scenario's are not incorporated in the current version of this model.

5. Maintenance

The maintenance of each vessel is taken into account using a semi-fixed maintenance schedule. Each vessel gets the same maintenance schedule but with a slight phase angle in respect to each other. Though its 30 year life cycle a vessel will encounter three different sorts of maintenance. Respectively small, medium and a large maintenance. The large maintenance is also know as a large vessel upgrade around the halfway point of the vessel's life cycle. Table 3.3 shows the values that are used for docking frequency and duration for each of these types of maintenance.

Table 3.3: Maintenance parameters for small, medium and large maintenance.

	Small	Medium	Large
Docking frequency [years]	1	3	15
Docking duration [years]	0.25	0.5	2.5

Figure 3.3 shows an example of the maintenance schedule of a fleet of 15 vessels over a simulation time of 1470 days. The y-axis shows the total number of vessels in maintenance. The blue line in figure 3.3 relates to the semi-fixed statement from earlier. When a vessel is doing a mission while it is supposed to go in maintenance the schedule for that particular vessel will shift the same amount of days as the remaining time of the

mission.

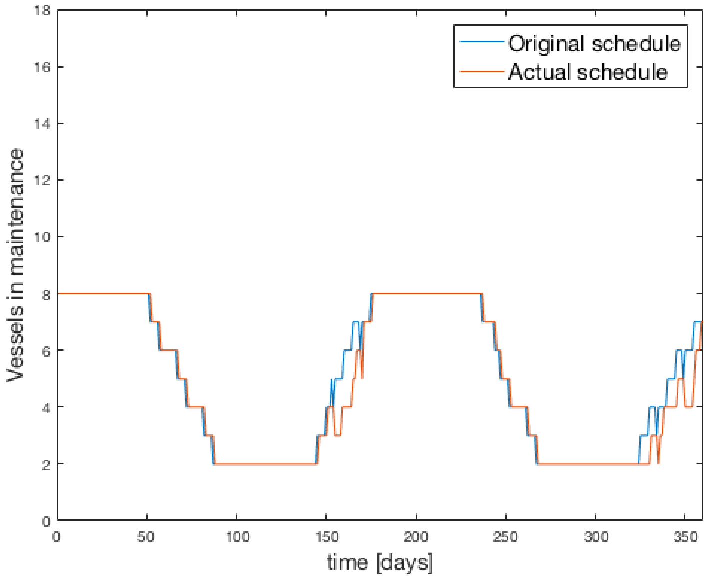


Figure 3.3: Maintenance schedule.

6. Opposition modelling

The opposition has been mentioned a lot up until this point in the report. This section will elaborate on how this separate entity is handled in the model.

In *Fleet Tactics and Coastal Combat* [6] Hughes describes the operation of a naval entity as depicted in figure 3.4. This figure describes the continuous process of how any kind of entity, whether it is a person, single vessel or an entire fleet, that tries to get to, and remain in a desired state. This system shares a lot of similarities with a simple control system.

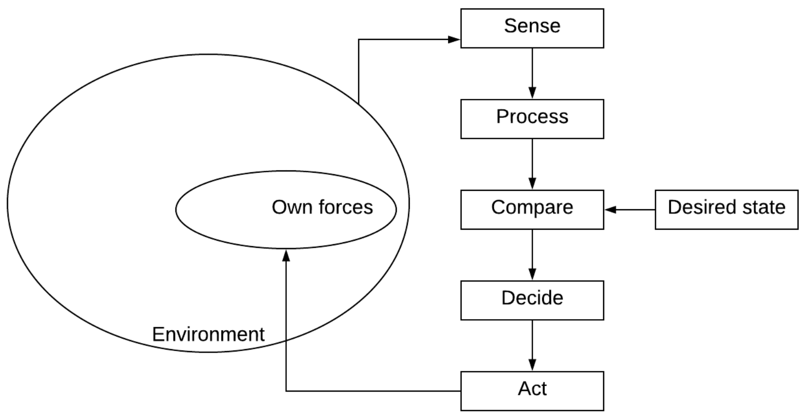


Figure 3.4: Hughes' model depiction.

If we look at this from a fleet perspective where the fleet functions as a unit, the environment would be the physical location of the fleet. Information about the environment could be the weather, sea state, location, enemy presence, state of the supplies, and more. These parameters are observed using different sensors, for example radar, sonar, and gps but also the human eye. All this information is processed before it is compared to the desired state. Based on this comparison is decided if there is an offset between the current state and the desired state. If there is an offset an action is required to push the current situation towards its desired state.

To give a very basic example: in the scenario where a fleet is collectively sailing to a specific location, the observable data of importance comes from the GPS and potentially visual clues when sailing near the shore. This information is processed into a current location after which these coordinates are compared to the desired state i.e. the destination. If the fleet is not at the destination yet there will be an offset between the current state and the desired state. This gives the crew a few choices, in this example these can be whether to continue at the current speed, increase the speed or lower the speed, depending on the desired time of arrival. What follows is the act of actually changing the speed. This process loops indefinitely.

The depiction shown in figure 3.4 works well for single intelligent agent systems. These are systems where only one intelligent entity acts upon its environment through sensors and actuators. When trying to model a confrontation, whether it is naval or otherwise, we have two intelligent entities acting not only on the environment but also upon each other. In other words, the acts of one will influence the other.
However both entities still have to comply to the same set of rules and will have to go through the same processes in order to act. Therefore we can depict this system by mirroring figure 3.4. This new "full" depiction is shown in figure 3.5.

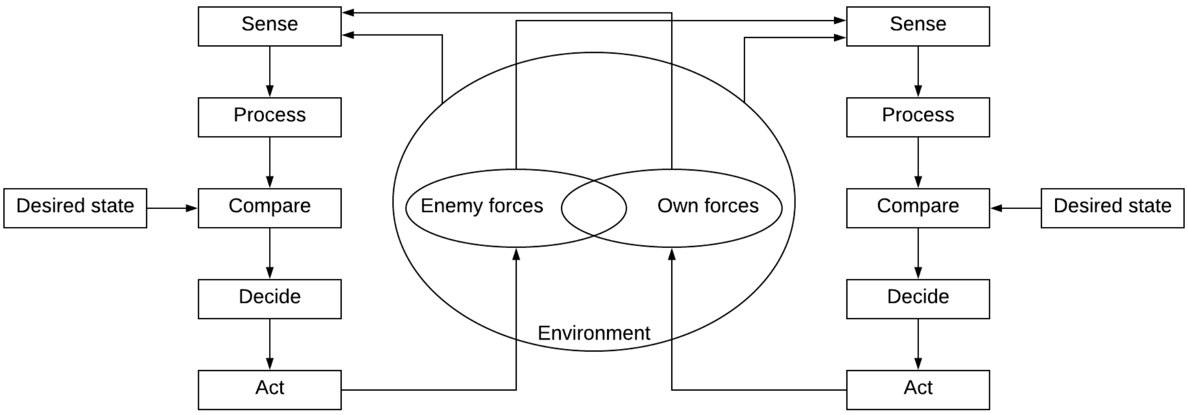


Figure 3.5: Hughes' model depiction full picture.

Figure 3.5 shows that in a battle scenario both fleets will go through the same set of processes. However the desired state may differ. In general, the fleet that is able to go through this set of processes more efficiently comes out on top.

From this depiction follows the implementation of enemy fleets in this particular fleet behaviour model. Enemy vessels are generated in the exact same way the own fleet is generated. The fleet is given a size and individual vessels are given a speed, location and maintenance schedule. Furthermore vessels are given warfare capabilities using Hughes' Salvo parameters. The enemy fleet is only used for simulating battle scenarios to therefore incorporate attrition into the mix, for this reason enemy vessels are not assigned to specific types and thus won't have mission capabilities. This data would be needed if enemy missions also need to be modelled. This could be useful to incorporate reactive type mission where the enemy has a specific objective that you want to prevent. As of now all missions are generated with our own fleet as the initiator.

Of course, this is not a simulation of one fleet against the world. Enemy vessels can come from different enemies. To incorporate this within the select view locations that are used in this simulation, regions are made. These regions are anything but realistic but that is not the point of this implementation. The point is to show that it is possible to incorporate different enemies and that the actions of your fleet have an influence on their future capabilities, just like their actions will have an influence on our fleets future capabilities. Splitting the enemy vessels over different enemies also allows for implementing diversity in enemy strength. Table 3.4 shows which mission location is assigned to which region, either the northern or the southern region.

Table 3.4: Enemy regions

Location	Region
Den Helder	N/A
Libya	South
Syria	South
Malta	South
Estonia	North
Germany	North

Each region has its own fleet which has its own size, capabilities and mission locations. So when executing a mission in Libya the opposing vessels that are encountered belong to a different fleet then when a mission in Estonia is executed. This concept is further extended by tracking the enemy vessels in the same manner as done with our own fleet. So when enemy vessels are destroyed their total fleet size gets smaller. Also, when a vessel is still fighting at one mission location it won't be available to fight at a different location.

7. Verification

At this point all aspects of the Fleet Behaviour Model have been discussed. However, before any results that are generated can be trusted first the model needs te be verified. By verification it will become clear whether the models and calculations in the behaviour model are implemented correctly.

Figure 3.6 shows a general description of the model.

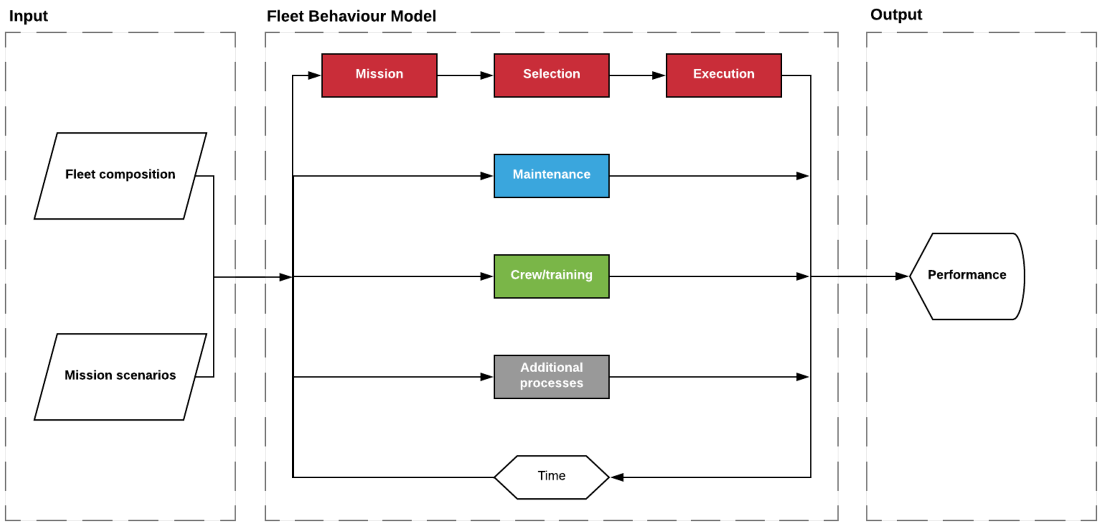


Figure 3.6: Model layout description.

To be able to verify whether the output makes sense a fixed input is used to simulate the fleet behaviour over one year. The mission scenarios that are used is shown in the appendix in table A.1. For the fleet composition a wide spread of the available vessel types is preferred to avoid an initial bias in the resulting output. Other than that the actual vessels that are used should have no influence on verifying the performance of this particular composition. The fleet composition that is used for this verification run is [3,3,3,3,3,3,3], so the complete fleet consists of 3 vessels for every 7 vessel types totalling a fleet size of 21 vessels.

The first output given by the fleet behaviour model is shown in Figure 3.7. This figure shows a general overview of the fleet status over the simulated time. It specifies for each day how many vessels are available for selection, in transit, executing a mission, resupplying, in maintenance and how many vessels are destroyed. This is a helpful tool to see at a quick glance how well the fleet performed. From Figure 3.7 a couple of conclusions can be made:

- Vessels are never in two places at the same time. Otherwise the fleet size would not be consistent.
- The maintenance schedule works as intended. The same trend as shown in Figure 3.3 can be found in Figure 3.7. Also, the discrepancies in that same trend show where the maintenance schedule needed to be moved because a vessel that needed to go in maintenance was on a mission at the time.
- Vessels that are destroyed are indeed lost for the remainder of the simulation and put the expected strain on the rest of the fleet.This follows from day 222 in the simulation where 2 vessels are lost. For the remaining simulation time the existing trend in the fleet status gets squashed, meaning that less vessels are available for selection at any given moment in time making it harder to successfully execute future missions.

The conclusions may seem very straight forward but the fact is that they still need to be confirmed before being able to successfully verify that the entire model works as intended.

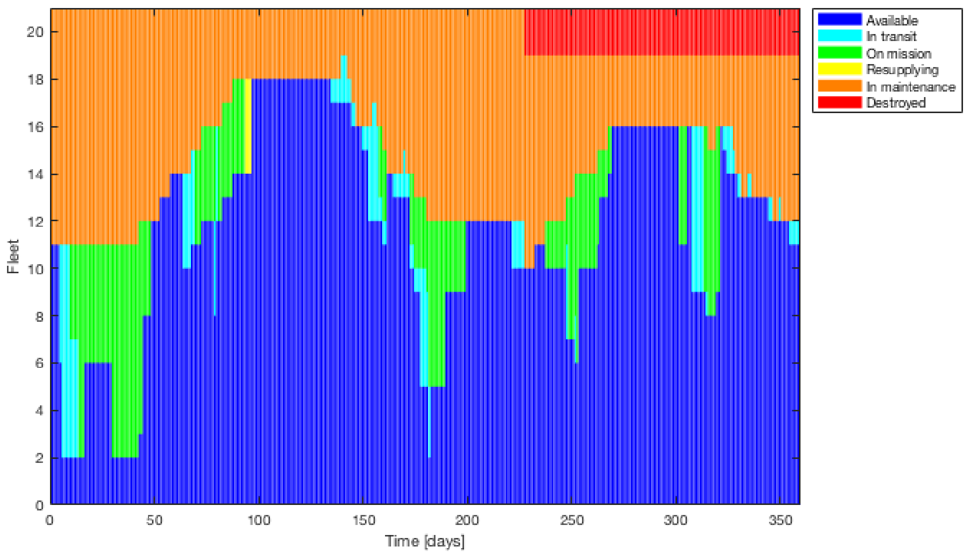


Figure 3.7: Fleet status over simulated time.

What Figure 3.7 does not show is whether the missions execution and vessel selection for those missions is handled correctly. For that additional information is needed, first of which is shown in table 3.5. This table shows for each mission the vessels that are selected and whether the mission execution was successful or not. If a particular mission failed this table also gives a brief summary of the reason. These reasons are a direct result from the selection and execution process depicted in Figure 3.2. Four missions are selected, one for each different mission result, to investigate further and see if the overall execution performs as expected. The chosen missions occur on days 5, 10, 79, and 222.

Table 3.5: Mission results summary

Mission day	Selected vessels	Mission result
5	Submarine, Submarine, LCF, Patrol, CSS	Success
6	LPD, LPD, M-Frigate, M-Frigate	Success
10	-	Failed: Can not meet mission requirements
30	LPD, LPD, M-Frigate, M-Frigate	Success
64	M-Frigate, M-Frigate, Patrol, JSS	Success
65	-	Failed: Can not meet mission requirements
79	LCF, M-Frigate, JSS, JSS	Failed: Battle undecided.
153	LPD, LCF, CSS	Success
173	LCF, M-Frigate, Patrol	Success
178	Submarine, Submarine, Submarine, CSS	Success
182	LPD, Patrol, JSS	Success
222	Submarine, M-Frigate	Failed: Battle lost.
238	Submarine, CSS	Success
248	LPD, LCF, M-Frigate, Patrol	Success
252	M-Frigate, Patrol	Success
302	LPD, LCF, M-Frigate, M-Frigate, JSS	Success
308	Submarine, LPD, LPD, LPD, M-Frigate, M-Frigate, CSS	Success

Table 3.6: Vessel type capability matrix

	Landing	AAW	ASuW	ASW	Supply
Submarine			X		
LPD	X				
LCF		X			
M-Frigate		X	X	X	
Patrol			X		
JSS	X				X
CSS					X

The first mission to be analysed occurs on day 5. This mission was successfully executed using a total of 5 vessels. Namely 2 submarines, 1 LCF, 1 patrol vessel, and 1 CSS. Table A.1 shows that the mission location is Syria and the required capabilities are: Anti-Air Warfare (AAW), Anti-Surface Warfare (ASuW), and Supply. Furthermore an enemy fleet of 3 vessels is expected to be on location. From table 3.6 follows the combined capabilities of the selected vessels. Combined the available capabilities for this mission are: 1x AAW, 3x ASuW, and 1x supply. So the required capabilities from the mission are not only met but exceeded. The excess capabilities come from the additional 2 vessels that have been selected in order to overcome the expected opposition at location, therefore resulting in a total of 5 vessels.

After 9 days of transit the vessels arrive in Syria where they encounter an opposing fleet of 4 vessels. So the intel on the enemy fleet was wrong since it was expected to consist of only 3 vessels. Table 3.7 shows a summary of this battle which is simulated using Hughes' Salvo Model. Each line shows the state of both fleets after a missile salvo. The first line is the starting situation. The other parameters represent:

FleetA	=	The number of vessels selected for the mission.
FleetB	=	Enemy fleet.
Off_AmmoA	=	Mean offensive ammunition on selected vessels.
Off_AmmoB	=	Mean offensive ammunition on enemy fleet.
Def_AmmoA	=	Mean defensive ammunition on selected vessels.
Def_AmmoB	=	Mean defensive ammunition on enemy fleet.

Table 3.7 shows that the selected vessels indeed win the battle. In this case it takes 2 salvo's to eliminate the enemy fleet. During each salvo every vessel launched 2 missiles which can be seen in the decrease of the offensive ammunition. For this battle the same was true for the defensive ammunition. Since after the battle the remaining ammunition, both offensive and defensive, are above the threshold of 10 missiles there is no need to resupply. Next the fleet continues the mission which in the model is represented by the required time on location (represented by the ToL value in Table A.1).For this mission the required time on location is 30 days. So since the mission occurred on day 5, after which the vessels needed 9 days to get to the mission location and a required time on location of 30 days, means that these vessels are available again on day 44. This is confirmed by the data and can also be seen in Figure 3.7 where at day 44 the amount of available vessels makes a jump from 3 to 8.

Table 3.7: Hughes' Salvo model results for a successful battle.

Salvo	FleetA	FleetB	Off_AmmoA	Off_AmmoB	Def_AmmoA	Def_AmmoB
0	5	4	15	10	36	22
1	5	2	13	8	34	20
2	5	0	11	6	33	17

The second mission to be analysed occurs on day 10. According to Table 3.5 this mission is failed because the missions' capability requirements can not be met. According to Figure 3.7 only 2 vessels are available on day 10. Only 1x JSS and 1x CSS. Combined these vessels have 1x landing and 2x supply capabilities. Since the required capabilities for this mission are: AAW, ASuW, and ASW it is correct that on day 10 these requirements can not be met. Therefore no vessels are selected and the mission is considered to be failed.

The next mission to be analysed occurs on day 79. According the mission results in Table 3.5 this mission failed because the battle was undecided. This means that both fleets were equally matched and all fired missiles from both sides missed or were deflected resulting in no damage being dealt for every single salvo. For this reason the ammunition parameter is included in the Hughes' Salvo Model to prevent the model from getting stuck in an infinite loop. However before checking the battle simulation first the vessel selection is verified. The required mission capabilities are AAW and ASW. For this mission four vessels are selected, 1x LCF, 1x M-Frigate, and 2x JSS. Combined these vessels have the following capabilities: 2x AAW, 1x ASuW, 1x ASW, and 2x supply capabilities. This shows that the required capabilities are more than met. In fact just to comply with the mission capabilities only a M-Frigate would have been needed. However, because of the expected opposition, consisting of 3 vessels 3, 3 more vessels are selected in effort to overcome them. Something not relative to the verification but on a side note: the fact that 2 JSS's are selected is of course far from realistic. This is due to the fact that the fleet has 3 combined with the basic assignment of capabilities to the different vessel types.

Table 3.8 shows the results fo the Hughes' Salvo simulation. This table shows that the intel of 3 opposing ships and an addition vessel is encountered on the mission location. After 9 missile salvo's no vessel of either side has been hit. However both fleets are out of offensive ammunition. In this case the model considers the mission as failed and the selected vessels will resupply at the nearest home base. This is also consistent with Figure 3.7 where resupplying is depicted in yellow.

Table 3.8: Hughes' Salvo model results for an undecided battle.

Salvo	FleetA	FleetB	Off_AmmoA	Off_AmmoB	Def_AmmoA	Def_AmmoB
0	4	4	17	16	34	27
1	4	4	15	14	32	25
2	4	4	13	12	30	23
3	4	4	11	10	28	21
4	4	4	9	8	26	19
5	4	4	7	6	24	17
6	4	4	5	4	22	15
7	4	4	3	2	20	13
8	4	4	1	0	20	12
9	4	4	0	0	20	11

The last mission to be analysed occurs on day 222. For this mission 1x Submarine and 1x M-Frigate have been selected. The required mission capabilities are AAW and ASW. Combined these vessels have 1x AAW, 2x ASuW, and 1x ASW capabilities. So the required capabilities are met. According to intel it is expected to encounter 2 opposing vessels. Table 3.5 shows that the mission was failed due to the fact that the battle was lost and the vessels destroyed. The reason for this lost battle can be concluded from the Hughes' Salvo Model results shown in Table 3.9. Again in this case the intel was off and an additional vessel was encountered on the mission location. Having a fleet of one and a half times the size the enemy fleet was able to destroy both vessels in one salvo. These vessels are lost for the rest of the simulation, this is depicted in Figure 3.7 by the red block.

Table 3.9: Hughes' Salvo model results for a lost battle.

Salvo	FleetA	FleetB	Off_AmmoA	Off_AmmoB	Def_AmmoA	Def_AmmoB
0	2	3	20	16	37	30
1	0	3	18	14	34	29

Having discussed all implemented processes of the Fleet Behaviour Model it can be concluded that the model works as intended.

8. Overview Fleet Behaviour Model

By now every aspect that is currently implemented in the Fleet behaviour Model has been explained. With the model done it is now time to use it. From here on out the Fleet Behaviour Model is handled like a black box with certain inputs and outputs.

For the inputs the user has the freedom to choose between several options. These options will be explained here, as well as the influence they will have on the output. The main inputs are:

- Fleet composition
- Missions over time
- Objective function weight-factors
- Simulation time

Fleet composition. This is the input that has the most interest in this research. one option is to choose the fleet composition as a fixed input. This allows to test how well a specific fleet performs with different mission scenarios, maintenance schedules and/or training schedules. A fixed input is given using a vector where each value represents the number of a specific vessel types in the fleet. These indices are specified as follows: [*Submarines; LPD; LCF; M-Frigate; Patrol; JSS; CSS*].

The next option is to enter a variable fleet composition into the model. In this case multiple fleet compositions can be tested against a specific scenario. Lastly, the fleet composition can be a partial fixed input. In this case all vessels in the fleet except for an X amount of vessels are fixed. By varying these vessel types it is possible to determine the best choice of vessels to be added to an already existing fleet.

Missions over time. Similar as the fleet composition, the mission over time can be a fixed input or variable input. In the case of the fixed input a pre-made mission file is used. This mission file contains the day on which a mission occurs as well as the location, requirements, and information on the possible opposition. Combining this with a variable or partially fixed fleet composition input will allow you to compare different fleets in a steady scenario.

When using a variable input, the missions are randomly generated where each day has a chance for a mission to occur. When this occurs the location, requirements and opposition will be generated. The chance of a mission occurring on each day is also adjustable by the user, but it should be mentioned that has a direct influence on the total simulation time. Doubling the mission chance will results in twice the amount of missions that need to be simulated and will therefore nearly double the total simulation time. Using a variable mission input is useful for testing the performance of one fleet in different and/or changing scenarios.

Objective function weight-factors. The objective function weight-factors are introduced in the optimization process as described in chapter 4. These are used to specify what you want your fleet to be optimized towards: Successfulness, attrition and/or fleet size. Section 4.2 will elaborate more on the implementation of this particular input.

Simulation time. This input speaks for itself. The reason it is still mentioned here is to note that this input as a linear relation to the run time of the simulation. So if you double the simulated days you also double the simulation run time.

Now for the outputs:

- Fleet composition
- Missions over time
- Performance

Fleet composition. Next to being an input the fleet composition is also an output of the model. In fact this is probably the most important output as it gives the optimized fleet composition for one or multiple scenarios. Next to the most optimized all less suitable compositions that have been generated are also contained in this output for later reference.

Missions over time. Just as the fleet composition, the missions over time matrix is both an input as an output. However this output is only relevant when the input is chosen to be randomly generated. In that case this output gives a matrix containing the missions that have been generated so the user can manually check if the resulting fleet composition makes any sense.

Performance. The last significant output to be mentioned here is the performance parameter. This parameter tries to give a value to how well the chosen fleets perform within a scenario. This parameter is obtained using the objective function as will be described in chapter 4.

4

Optimization

Now the fleet behaviour is described in a model it is time to look for fleet compositions that best fit certain scenarios. This can be done by running a lot of different fleet compositions in the Fleet Behaviour Model while using the same set of mission scenarios. By comparing the resulting performance of each of these fleet compositions it is possible to find the best fleet composition for one specific set of mission scenarios. Defining each possible fleet composition by hand would take too much time so some sort of algorithm is required. One possibility would be to use the "brute force" strategy, where every single possible fleet composition within a certain range is automatically entered as input and then tested using the Fleet Behaviour Model. However, one run with a simulation time of 4 years can take up to 30 seconds to calculate. This would mean that using the brute force approach it would take over 18 years to run all possible fleet composition where each vessel type can occur between 0 and 10 times in any fleet. Therefore a smarter approach is needed. This is where optimization algorithms come in. These algorithm are designed to systematically vary the input parameters in such a way that not all possibilities have to be checked in order to find an optimal solution.

The different optimization methods that have been considered are: Genetic Algorithm (GA) [2], Markov decision process optimization [12], and Integer Linear Programming (ILP) [2]. Although the specific optimization method will influence the processing time of the simulation, it will not have any influence on the solution that it produces. In the end a choice was made to use a Genetic Algorithm. The implementation of this GA is described in section 1. To be able to find the best solution the algorithm needs to know whether one particular solution is better than another, this is done using an objective function which will be discussed in section 2. Lastly, multiple test cases have been constructed which are described in chapter 5.

1. Genetic algorithm

A genetic algorithm can be described as an optimization method inspired by natural processes found in evolution. It uses operators such as mutation, crossover, and selection [2].

It works by first generating an initial population, which is generally a randomly generated set of solutions to the problem. Because this is done randomly it allows for the entire range of possible solutions (the search space) to be present in the model. The initial population size depends on the complexity of the problem and the available computational power. In highly complex problems this can be as high as thousands of possible solutions.

After generating the initial population it is time to simulate evolution by reproduction, selection, and mutation. This is done over multiple generations in an effort to eventually converge to an optimized solution. To generate a second generation population a pair of parent solutions is selected to "reproduce". A new solution "child" is created by randomly combining the parent solution parameters, or its "DNA". New parents are selected for each child, and this reproduction precess continues until a new generation is generated of the same size as the parent generation.

From this new total population, the combination of the parent and the child generation, only the best solutions are selected for breeding the next generation. In evolutionary terms this would be described as the survival of the fittest. This process of reproducing is repeated for multiple generations until the solution converges to an optimized solution. This is usually when the best solution no longer changes over the span of multiple generations because there is no better solution to be found.

The final process that is added to this mix is mutation. Mutation is used in non-linear problems to prevent the algorithm from getting stuck in local optima. When a child is created there is a chance of a mutation to occur. When this happens a part of its DNA is changed to a random new value. It is important to tune this mutation chance. A very small mutation rate may still lead to genetic drift, the disappearance of gene variations. A very high mutation rate may lead to the loss of good solutions. When this happens it will result in much longer calculation times.

Implementation

To explain how the GA works in this particular model an example will be used.
In this example the goal is to find an optimal fleet composition. Therefore the input of the GA is the fleet composition. This composition is given using a vector where each entry represents a certain vessel type. The order of this vector is arbitrary but it is important to use the same order throughout the simulation. The order that is chosen is: Submarine, LPD, LCF, M-frigate, Patrol, JSS, CSS. So an example of a fleet composition vector can be:

Example solution 1):
$$\begin{pmatrix} 3 & 2 & 5 & 2 & 1 & 6 & 4 \end{pmatrix}$$

So in this example the fleet consists of 3 submarines, 2 LPD's, 5 LCF's and so on.

So as explained in the previous section first a initial population is randomly generated and sorted on fitness. The fitness of a certain solution is calculated using an objective function and is designed to determine whether one solution is better than the other. The objective function that is used for this algorithm will be explained in detail in section 2 but for now it is important to know that it takes the mission success rate, the readiness, the attrition, and the size of the fleet into consideration.

As a first run the initial population size is set to 100. This means that to generate an initial population a random matrix needs to be generated of 100 by 7, 100 solutions by 7 vessel types. For now the Dutch navy is taken as a reference and since the the Dutch fleet can not be considered very big an upper limit of 10 vessels per type is used. This means that the absolute largest fleet that a solution can have is equal to 7 times 10, so 70 vessels. Next the fitness is determined for the all solutions in the initial population.

To explain the workings of generating the next generation of solution a second solution will be used:

Example solution 2):
$$\begin{pmatrix} 1 & 4 & 3 & 6 & 2 & 2 & 7 \end{pmatrix}$$

For this example solution 1 and 2 are selected as parents to reproduce and create 2 children for the next generation. First the specific genes for the cross-over are randomly selected. For instance genes 1, 3 and 7 are selected as one part and therefore the second part of the cross-over will contain genes 2, 4, 5 and 6. The first child with have genes 1, 3 and 7 from parent 1 and genes 2, 4, 5 and 6 from parent 2. The gene indices are highlighted in red and yellow for this example. So this will result in:

Child 1):
$$\begin{pmatrix} 3 & 4 & 5 & 6 & 2 & 2 & 4 \end{pmatrix}$$

Child 2 will get the opposite genes, so genes 1, 3 and 7 from parent 2 and genes 2, 4, 5 and 6 from parent 1. This will result in:

Child 2):
$$\begin{pmatrix} 1 & 2 & 3 & 2 & 1 & 6 & 7 \end{pmatrix}$$

After reproduction there is a 10% chance of a mutation occurring. When this happens child 1 or 2 will be randomly selected and one random gene will be given a new random value. For example: a mutation could occur in child 2 where gene 1,coloured red, will change into a new value between 0 and 10.

Child 2 after mutation):

$\begin{pmatrix} \color{red}{9} & 2 & 3 & 2 & 1 & 6 & 7 \end{pmatrix}$

The reproduction phase continues until all solutions in the parent have generated new children. Since every 2 parents make 2 children the new population is twice as big as the initial population, in this case it consists of 200 solutions. To get it back to the original population size selection on fitness is used. For all children the fitness is calculated after which the entire population is ordered on there fitness. Only the best 100 will be used to generate the next generation. In this simulation parents are also able to be part of the next generation if their fitness value is among the 100 best solutions. This process continues until the best solution converges.
The convergence of a run is shown in figure 4.1.

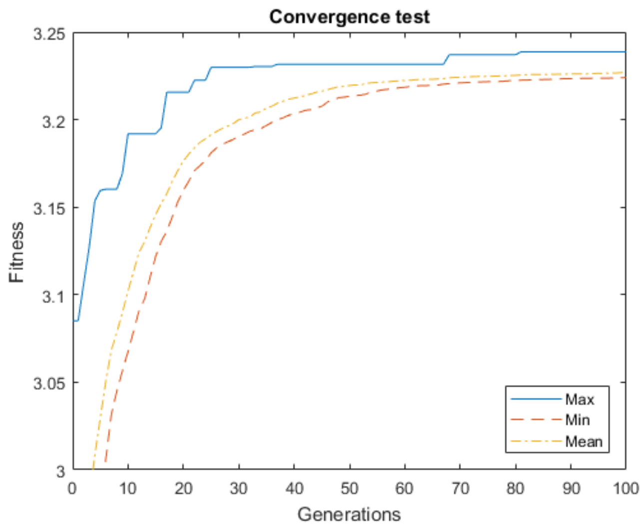


Figure 4.1: Convergence test.

Figure 4.1 shows how the most optimal solution of each generation over a run of the optimization model changes. The most optimal solution is the solution that has the highest objective function value and is depicted as the max line. For contrast the worst and mean solutions over all generations are also plotted. This run is done using fixed parameters where possible to make sure the results can be reproduced. This means that the missions over time, enemy strength, intel quality, and initial fleet location are fixed instead of random.

The decrease in change of the most optimal solution shows that the solution converges at around the 85th generation. This shows that running for at least 100 generations for each simulation is necessary. However, if the population size can be cut down the calculation time would decrease linearly. Therefore this is something worthwhile to find out before additional runs are made. Figure 4.2 shows 5 additional runs with the same presets except for having a population size of 50 instead of 100. 5 Runs are done to make sure the results are consistent.

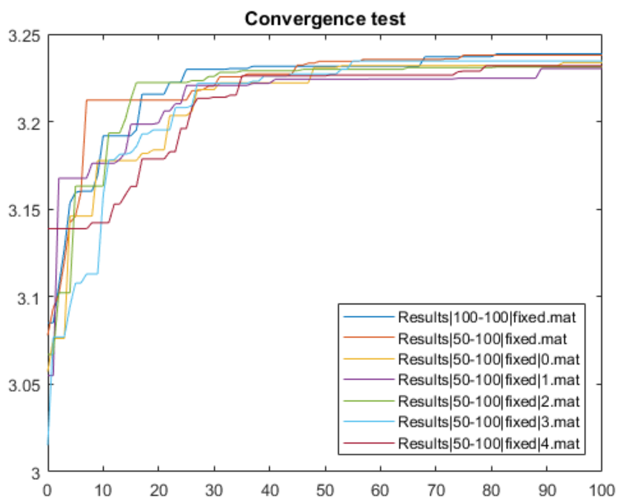


Figure 4.2: Convergence test with half population size.

Figure 4.2 shows that using a population size of 50 instead of 100 gives the same resulting fitness within a range of 0.02. However by cutting the population size in half, the calculation time of an individual run is also cut in half. Bringing it from roughly 4 hours back to 2 hours. This is why for the rest of the simulations a population size of 50 is used.

2. Objective function

As stated before objective function is used to determine whether one solution is better than another. For this problem it tries to encapsulate how well a fleet performs in aspects that are valuable to navies in general. These aspects are:

- Mission successfulness. Whether missions are generally executed successfully.
- Attrition. Whether vessels are lost in combat during the simulation period. This term especially can be highly dependent on different scenarios. In wartime attrition is usually inevitable while in peacetime this tends to be unacceptable.
- Fleet size. This term is used to prevent the model from generating a huge armada. Of course having a bigger fleet will give you a higher chance of success but this is not always realistic.

By using these three aspects the following objective function is made.

$$O = c_1 \cdot \underbrace{\frac{Success - Failed}{Success + Failed}}_{\text{Mission successfulness}} - c_2 \cdot \underbrace{\frac{\text{vessels lost}}{N}}_{\text{Attrition}} + c_3 \cdot \underbrace{\frac{70 - N}{70}}_{\text{Fleet size}}$$

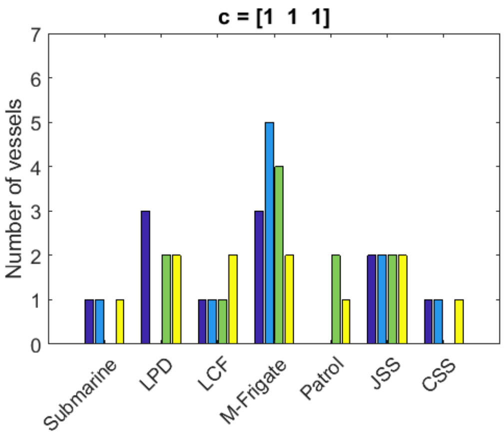
Where:

$Success$	=	The number of successfully executed missions of the simulation time.
$Failed$	=	The number of failed missions of the simulation time.
N	=	The initial fleet size.
vessels lost	=	The number of vessels lost in combat over the simulation time.

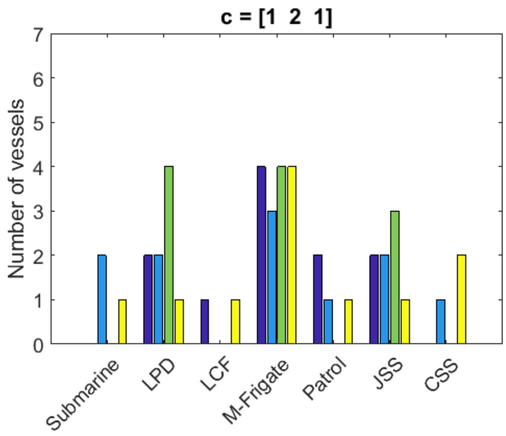
The objective function contains three terms for the three different important aspects as mentioned above. Each of the terms are made to be dimensionless so they all will have the same impact on the fitness value that results from this objective function. However all terms have a weight-factor, respectively c_1, c_2 and c_3. This weight-factor is used by the user to differentiate in terms based on there importance and thereby steer the solution. By giving a term a higher weight-factor that term becomes more important for the eventual fitness value and the model will therefore put more emphasis on this term. Since the importance of these terms respectively to each other also highly depends on the situation, this weight-factor vector can also be used in differentiating between different scenarios like war and peace time.

3. Verification

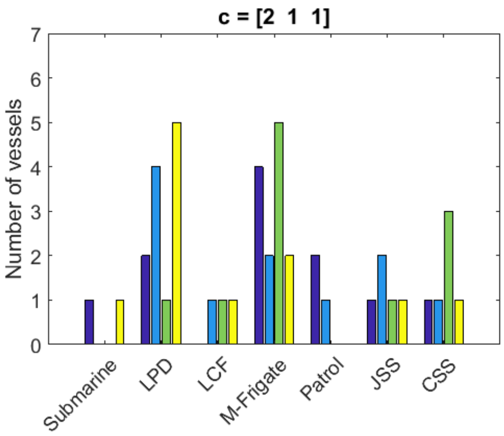
To make sure that the outcome can actually be influenced by changing the weight-factors a small study is done. Initially using 4 different sets of weight-factors test-runs are done to see if the resulting fleet composition changes and if yes, if this can be explained given the mission set. The mission set that was used for this study is shown in appendix A. The first results are shown in the graphs of figure 4.3.



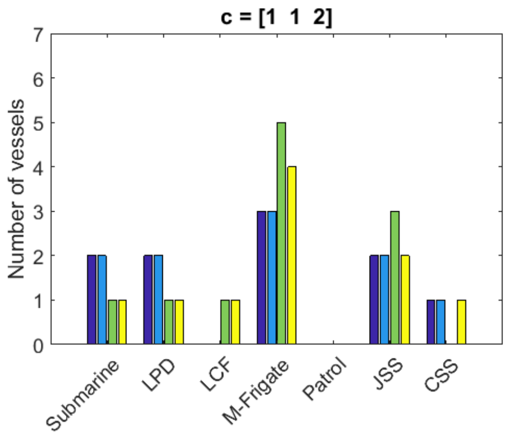
(a) Fleet composition for $c = [1, 1, 1]$.



(b) Fleet composition for $c = [1, 2, 1]$.



(c) Fleet composition for $c = [2, 1, 1]$.



(d) Fleet composition for $c = [1, 1, 2]$.

Figure 4.3: Generated fleet compositions for different weight-factors.

The bar graphs in figure 4.3 shows for each vessel type how many are in the generated fleet composition. Next to the vessel types the fitness value, mission successfulness, attrition, and fleet size are also displayed. The fitness value is obtained by the objective function and the mission successfulness value represents the percentage of successful completed missions out of all generated missions. The attrition is given in number of vessels lost and lastly the fleet size is given as shown in the objective function, an inverted percentage of the maximum fleet size of 70 vessels.

For each set of weight-factors for simulation runs are done to see if the resulting fleet compositions are consistent. Each run is represented as a different colour in the bar graphs. This is where the bar graphs become useful because it is now easy to see how consistent the output is.

Figure 4.3 shows that there is a definite trend in the results. This means that changing the priorities of the fleet results in a different optimal fleet. However the consistency is not perfect. Especially the simulations with the weight-factors $c = [2, 1, 1]$ (4.3c), where priority is given to mission successfulness, shows some large deviations. These deviations are probably caused by some of the decisions that have been made while making this model. The first of which is the choice to use a genetic algorithm. As discussed in section 1 of this chapter, this type of optimization methods have the possibility to get stuck in local optima. This can happen with highly non-linear problems such as this one.

Another reason for the inconsistencies in the resulting fleet compositions can be the random generated values given to some of the parameters throughout the simulation. Most random assigned values have been eliminated specifically for this sensitivity study, such as the intel quality and the vessel starting location. However each vessel still get a randomly assigned cruising speed within a range. This could make the difference between selecting one combination of vessels for a mission in one simulation and another for that same mission in the next simulation. What makes this problem more significant is the fact that all simulations are done for a 1 year time span. This choice was made for time restricting reasons, the 4 runs for 1 simulation (1 of bar graphs) takes 8 hours to simulate. The shorter simulation time of 1 year makes the difference in results from one mission significantly more influential than when simulating a time span of 4 years for example, resulting in a (slightly) different optimal fleet composition.

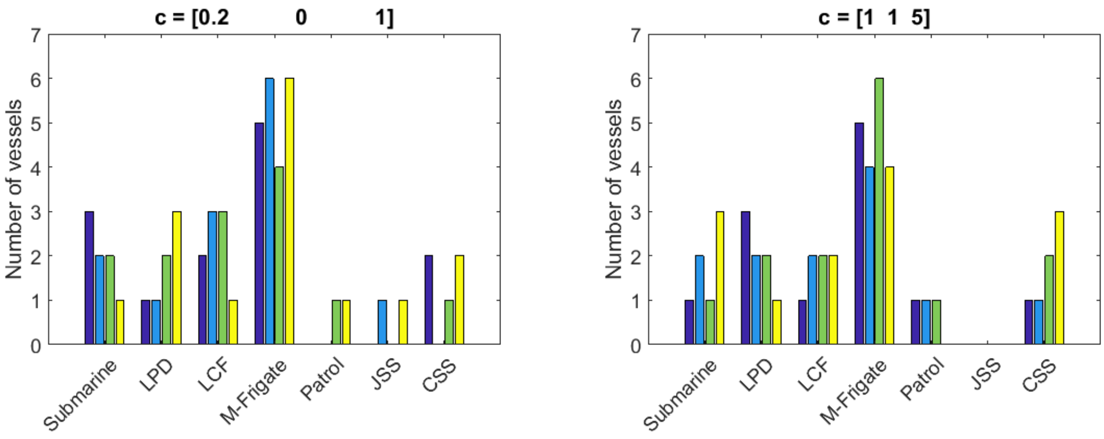
That being said, the point of this sensitivity study is to see if prioritizing different aspects from a fleet perspective will actually result in a different optimal fleet from the model. This is easier to conclude when comparing number instead of the bars in a bar graph. Therefore table 4.1 is made which shows the mean value of the number of vessels and objective function values shown in the figure 4.3.

Table 4.1: Mean sensitivity results. (c = [Mission successfulness, Attrition, Fleet size])

c	Sub	LPD	LCF	M-Frigate	Patrol	JSS	CSS	Fitness	Success rate	Attrition	Fleet size
$[1,1,1]$	0.75	1.75	1.25	3.5	0.75	2	0.75	1.85	100 %	0	10.75
$[1,2,1]$	0.75	2.25	0.5	3.75	1	2	0.75	1.84	100 %	0	11
$[2,1,1]$	0.5	3	0.75	3.25	0.75	1.25	1.5	2.84	100 %	0	11
$[1,1,2]$	1.5	1.5	0.5	3.75	0	2.25	0.75	2.71	100 %	0	10.25

The first thing to note in table 4.1 is that the baseline test, where all weight-factors are equal, already has a mission successfulness of 100 %. This means that during the 1 year simulation period all the missions have been successfully executed for all runs. This indicates that the fleet behaviour model is doing a good job in selecting the right vessels for a mission and the optimization model is adapting the fleet composition to the applicable set of missions. However from a sensitivity standpoint this is not ideal. Since we already have a 100 % mission successfulness there is no way to show that focussing on this aspect will yield better results in general. The same goes for the attrition, since no vessels are lost in any of these initial runs there is no way to do better by changing the weight-factors. However, from these first four runs we can at least conclude that the by giving the priority to fleet size, [1,1,2], the optimized fleet will actually become smaller.

To see the influence of the mission successfulness and attrition factors additional tests were needed. Because of the way the selection process is programmed these two parameters are linked in some ways. As described in section 3.3, the selection progress is highly focussed on selecting the correct vessels to execute the mission successfully. If based on the intel it is expected to loose the vessels the mission is cancelled and seen as failed. So a mission can be failed without the loss of vessels, but not the other way around. If the vessels are lost the mission is also failed. Due to this one way connection between mission successfulness and attrition more extreme values for the weight-factors were needed in this test case to result in an optimal solution where vessels are lost. The sets of weight-factors that have been chosen in an attempt to loose some vessels and reduce the success rate are: [0.2, 0, 1] and [1, 1, 5]. The results of these runs are shown in figure 4.4.



(a) Fleet composition for $c = [0.2, 0, 1]$.

(b) Fleet composition for $c = [1, 1, 5]$.

Figure 4.4: Additional fleet compositions.

Figure 4.4a shows that vessels can be lost by using a weight factor value of zero for the attrition combined with a relative high priority on the fleet size and low priority on the success rate. This set of weight-factors is not realistic in any way and is only created to show that the attrition in the model works. The fleet size needs to be prioritized to push the model to create a smaller fleet and the success rate needs to have a low priority in order to make loosing a mission more acceptable to the model. The mean results of these tests are again given in a table, namely table 4.2. This time all additional results have been added to the previous to give one overview of all sensitivity study results.

The next test run, figure 4.4b, is done to test how sensitive the attrition weight-factor really is. This figure shows that by changing the this value from 0 to 1 all attrition is lost, proving that this factor is highly sensitive. Apart from loosing the attrition this test also shows that striving for a smaller fleet will negatively influence the mission successfulness, which makes a lot of sense if you think about it. Having fewer vessels to send on mission will ultimately result in not being able to execute all missions.

The last test run is depicted in figure 4.5. This run is done to test if multiplying all weight-factors by the same value, therefore keeping the same relative to each other, will result in the same fleet composition. Of course this will change the fitness value something completely different since higher values are used, however figure 4.5 and table 4.2 show that the resulting fleet composition is still almost the same. The small difference can be explained by the few random factors still in the simulation as discussed before in this section.

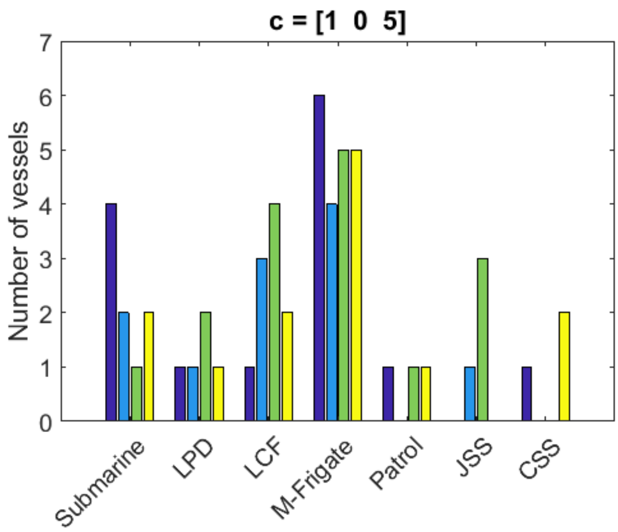


Figure 4.5: Fleet composition for $c = [1, 0, 5]$.

Table 4.2: Mean sensitivity results including additional runs. (c = [Mission successfulness, Attrition, Fleet size])

c	Sub	LPD	LCF	M-Frigate	Patrol	JSS	CSS	Fitness	Success rate	Attrition	Fleet size
$[1,1,1]$	0.75	1.75	1.25	3.5	0.75	2	0.75	1.85	100 %	0	10.75
$[1,2,1]$	0.75	2.25	0.5	3.75	1	2	0.75	1.84	100 %	0	11
$[2,1,1]$	0.5	3	0.75	3.25	0.75	1.25	1.5	2.84	100 %	0	11
$[1,1,2]$	1.5	1.5	0.5	3.75	0	2.25	0.75	2.71	100 %	0	10.25
$[0.2,0,1]$	2	1.75	2.25	5.25	0.5	0.5	1.25	0.94	84 %	2	13.5
$[1,1,5]$	1.75	2	1.75	4.75	0.75	0	1.75	4.68	79 %	0	12.75
$[1,0,5]$	2.25	1.25	2.5	5	0.75	1	0.75	4.71	84 %	1.25	13.5

5

Test cases and Results

This chapter will focus on the case scenarios that have been constructed with the goal to test the capabilities of the finished model. Next to testing the model, these test cases will provide an answer to the original problem statement. In chapter 2 the problem statement was distilled into three research questions that the finished model should be able to answer:

1. Find an optimum fleet composition for a given set of scenarios. This should give insight into the kind of fleet to strive for in the long term.
2. Given the example situation where a budget is available to invest in new vessels, lets say submarines. From this budget it is possible to buy a couple large submarines or more smaller ones. The finished model should be able to give insight into which of the two option is better from a fleet effectiveness perspective.
3. The finished model should be able to test one specific fleet against a wide range of scenarios. This should give a handle on the versatility of that specific fleet.

In order to test these statements three test cases have been constructed, one for each statement.

1. Test case 1: Find winning fleet.

This first test case is designed to test the model in its ability to find an optimal fleet for a specific scenario. In other words, this checks whether the model can actually generate a fleet that contains the correct collection of capabilities and distributes these capabilities well over the fleet by using the different vessel types.

For this case two sets of missions scenarios are tested. One wartime scenario and one peacetime scenario. The mission inputs are fixed and are separately generated beforehand. The wartime and peacetime simulations are discussed separately, starting with the wartime scenario.

Wartime scenario

For the wartime mission scenario the following input parameters are used in order to generate the input matrix:

Mission chance	=	10%	;	Every day has a 10% chance for a mission to occur.
Intel quality	=	random	;	The intel has a random offset to the original enemy fleet capabilities before each confrontation.
Simulation time	=	1460	;	The total simulation time is 1460 days (4 years).

The random intel is needed in order to incorporate attrition into the model. If this random change is excluded the model will know when a battle can not be won and will therefore never send any vessels. To overcome this a random change is applied to the enemy fleet parameters, as shown in tables A.2 - A.6, between the moment specific vessels are selected for a mission and the moment they arrive.

The resulting mission scenario contains a total of 172 individual missions, which all can be found in tables A.2 - A.10. Since this table is too long to show here a short summary of the key parameters is presented here. Below the occurrence of each required capability and the sum of missions on each location is shown.

Landing	:	63 times	Libya	:	42 times
Anti-Air-Warfare	:	73 times	Syria	:	40 times
Anti-Surface-Warfare	:	69 times	Malta	:	23 times
Anti-Sub-Warfare	:	75 times	Estonia	:	36 times
Supply	:	71 times	Germany	:	31 times

Lastly, the average time on location is 16 days and the average enemy fleet size encountered during these missions is 1.85.

The fleet composition is a variable vector input, of which the syntax is: *[Submarine, LPD, LCF, M-frigate, Patrol, JSS, CSS]*. The genetic algorithm is used to find an optimal fleet composition for this mission scenario. Since this test case simulates a wartime scenario the optimization priority is set to prioritize the mission successfulness. Since the amount of missions and consequences of these missions in wartime generally rises so does the budget of the navy. Therefore the fleet size weight-factor can have a smaller value allowing the model to converge towards a bigger fleet. The priority is set using the weight factors in the objective function, $[c_1, c_2, c_3]$ = *[mission successfulness, attrition, fleet size]*, and is set to *[3,1,1]*.

The simulation is run twice in order to see the consistency of the results. Table 5.1 shows the resulting fleet compositions, one for each run of the same wartime scenario.

Table 5.1: Resulting fleet composition test case 1. War scenario.

Run	Sub	LPD	LCF	M-Frigate	Patrol	JSS	CSS
1	7	7	6	8	8	8	7
2	7	7	6	8	8	8	7

Table 5.1 shows that both runs came up with the same fleet for the war scenario. From these compositions it can be concluded that for a wartime scenario a larger fleet is needed in order to stay effective. This is to be expected given the fact that the wartime scenario contains a large amount of missions. Having a larger fleet ensures that at all times suitable capabilities are still available for selection when a large portion of the fleet is already assigned to a different mission or in maintenance.

Summing up all the capabilities of the different vessels gives the total fleet capabilities. Table 5.2 shows the fleet capabilities for the fleets of this first test case.

Table 5.2: Fleet capabilities.

Capability	Landing	AAW	ASuW	ASW	Supply
Occurrence	15	14	23	8	15

Table 5.2 shows how many times each capability is present in this fleet composition. Since the capabilities required by the mission over time in this war time scenario test case have a linear relation to each other the

first hypothesis was that the fleet capabilities would have the same linear relation. However table 5.2 shows that this is not the case. The reason for this can be found in the definition of the different vessel types. Because the vessel types can contain multiple capabilities the distribution will never be the same as the required mission capabilities. The best example for this surrounds the M-frigate vessel type. Firstly, in this definition, the M-frigate is the only vessel that can perform Anti-Submarine Warfare (ASW). This means that every time an M-Frigate is added to the fleet composition just to acquire the ASW capability, also AAW and ASuW capabilities are added to the total fleet capabilities. And secondly the ASuW is the most occurring capability in the defined vessel types since it is the only one that occurs on more than two different vessel types, namely the submarine, M-frigate, and on the patrol vessel. These two factors combined account for the large amount of ASuW capability present in the fleet capability. This same effect is seen throughout all generated fleet compositions for the test cases and will be further analysed in Section 5.2.1.

In order to see what makes these fleet perform well it is compared to a non-optimal solution. The non-optimal fleet, [6, 5, 1, 5, 6, 7, 9] is arbitrary picked from the first generation. Table 5.3 shows the performance parameters of both fleets.

Table 5.3: Performance indicators for comparison test case 1.

Composition	Fitness value	Success rate [%]	Vessels lost
[7,7,6,8,8,8,7]	2.64	89	8
[6,5,1,5,6,7,9]	0.82	59	7

The first thing to note from table 5.3 is the big difference in fitness value. The fact that the attrition of both fleets is very similar and the non-optimal fleet is actually a lot smaller, 39 vessels compared to 51 vessels of the optimal fleet, suggests that this difference solely originates from the mission successfulness. Where the first fleet successfully executes 89% of the 172 missions, the second fleet only successfully executes 59%. Looking deeper into the distribution of reasons for mission failure between both fleets results in table 5.4.

Table 5.4: Distribution reason for mission failure for comparison test case 1.

Composition	Mission Requirements	Battle undecided	Battle lost	Expected loss
[7,7,6,8,8,8,7]	3	22	3	0
[6,5,1,5,6,7,9]	43	24	3	0

Table 5.4 shows that the main reason for mission failure for the non-optimal fleet is not being able to meet the mission requirements. From this it can be concluded that the non-optimal fleet has a collection of capabilities that is too small. In turn this results in a lack of capability availability throughout the simulation as a large portion of the fleet is already executing a different mission or is in maintenance.

Peacetime scenario

For the peacetime scenario a mission input is generated with less missions and a smaller chance of encountering an enemy fleet. The input parameters for generating this mission scenario that are used are given here.

Mission chance	=	3%	;	Every day has a 3% chance for a mission to occur.
Intel quality	=	random	;	The intel has a random offset to the original enemy fleet capabilities before each confrontation.
Simulation time	=	1460	;	The total simulation time is 1460 days (4 years).

The resulting missions scenario contains a total of 51 missions over a period of 4 years. The individual mission parameters can be found in tables A.11-A.13. The amount of times each capability is required over this period of time is shown below. Also the mission occurrence at each location is shown.

Landing	:	17 times	Libya	:	8 times
Anti-Air-Warfare	:	20 times	Syria	:	14 times
Anti-Surface-Warfare	:	23 times	Malta	:	8 times
Anti-Sub-Warfare	:	19 times	Estonia	:	10 times
Supply	:	23 times	Germany	:	11 times

Lastly, The average time on location is 15 days and the average enemy fleet size that is encountered during the missions is 1.5.

Just as the war scenario, also the peace scenario is run twice in order to see the consistency of the results. Table 5.5 shows the fleet compositions that result from this simulation. The final difference in input between the wartime and peacetime simulation are the weight-factors used in the objective function. Where for the wartime simulation the weight-factors [3, 1, 1] are used in order to prioritize mission successfulness, is for the peacetime simulation [1, 2, 2] used as weight-factor input. This prioritizes fleet size and attrition. The performance parameters change because in peacetime fewer missions occur lowering the urgency for having a naval fleet which in turn results in a smaller budget. In general this results in a smaller fleet and with a smaller fleet loosing a single vessel has bigger impact on the performance than for a bigger fleet where the loss is relatively smaller. Hence both fleet size and attrition are prioritized over mission successfulness.

The fleets composition generated by the peacetime simulation are shown in table 5.5.

Table 5.5: Resulting fleet composition test case 1. Peace scenario.

Run	Sub	LPD	LCF	M-Frigate	Patrol	JSS	CSS
1	2	2	1	4	0	1	2
2	2	1	2	4	1	3	1

Table 5.5 shows that although the fleet compositions that are generated for this test case are similar there are some small differences. As described in Chapter 4 these differences are the result from the random change over the intel and the small range in cruising speeds of the generated vessels. Furthermore the use of a genetic algorithm comes with the possibility of the model getting stuck in a local optimum instead of converging towards the global optimal solution.

Table 5.6 shows the fleet capabilities for both generated fleets. Just as with the war time scenario there is a peak in ASuW capabilities.

Table 5.6: Fleet capabilities.

Capability	Landing	AAW	ASuW	ASW	Supply
Occurrence	3	5	6	4	3
	4	6	7	4	4

The first thing to note when looking at tables 5.1 and 5.5 is the significantly smaller fleet that is generated for the peacetime scenario. Given that in the wartime scenario a total of 172 missions are encountered where in the peacetime scenario only 51 missions are encountered, combined with the fact that the model is discouraged to generate a fleet which is too large, this result is as expected.

When comparing these fleet compositions with a non-optimal solution from this simulation additional conclusions can be drawn. For this comparison the fleet from run 1 is used as the optimal fleet. The results from all encountered missions can be found in the appendix in table B.9. For the non-optimal fleet an arbitrary solution from the first generation is picked, this solution has the following fleet composition: [5, 1, 6, 8, 2, 2, 1]. The mission results can be found in the appendix in table B.10.

In order to compare the two fleets a summary of the performance is shown below. Table 5.7 shows for both fleets the fitness value, success rate, and the amount of vessels that are lost over the simulation period. The fitness value is the value that results from the objective function. The success rate gives the percentage of successful missions that have been executed by the fleet over the simulation period. Table 5.8 shows a distribution of the reason for mission failure for both fleets. This shows how many times a mission was failed for one particular reason. These reasons for failure are discussed in chapter 3 and can also be found in figure 3.2.

Table 5.7: Performance indicators for comparison test case 1.

Composition	Fitness value	Success rate [%]	Vessels lost
[2,2,1,4,0,1,2]	2.46	69	2
[5,1,6,8,2,2,1]	1.14	67	6

Table 5.7 shows that the optimal fleet has a fitness value that is more than twice as high as the non-optimal fleet. This table also shows that this difference does not result from the mission successfulness of either fleet since the success rate is similar. This is also confirmed by the information shown in table 5.8 which shows that no big differences occur in the mission execution.

Table 5.8: Distribution reason for mission failure for comparison test case 1.

Composition	Mission Requirements	Battle undecided	Battle lost	Expected loss
[2,2,1,4,0,1,2]	5	8	2	1
[5,1,6,8,2,2,1]	7	7	3	0

In the end the main reason why the optimal fleet is considered to be a better solution is the fleet size. This fleet manages to have the same mission successfulness while having 13 fewer vessels. This combined with the fact that during this particular simulation the fleet also looses 4 less vessels in battle makes this fleet superior during a peacetime scenario. Interestingly the inferior fleet will probably perform better in a wartime scenario due to its bigger number of vessels.

2. Test case 2: Find optimal additional vessels.

The second test case will test the model on optimizing a partly fixed fleet composition. This will represent the more realistic scenario where vessels of a certain type are outdated and need to be renewed. For this test case the submarines and M-frigates are kept as a variable input, the rest of the fleet composition is fixed. The input fleet composition that is used for this simulations looks as following: *[x, 2, 4, y, 4, 1, 1]*. In this composition x represents the variable number of submarines and y the number of M-frigates.

Each vessel type is limited to a maximum of 10 vessels in the total fleet composition. Therefore, this test case has a total of 11^2 possible solutions. Because this is a relatively small amount it is possible to use the brute force approach instead of having to use an optimization algorithm because of the processing time it takes. But even though the genetic algorithm is not used for this test case, the objective function is still used as an early performance indicator. The same weight-factors are used as in test case 1, [3, 1, 1] for the wartime scenario prioritizing mission successfulness and [1, 2, 2] for the peacetime scenario prioritizing fleet size and attrition.

Lastly, the same mission input for both the wartime and the peacetime scenarios are used as the ones in test case 1.

Tables 5.9 and 5.11 show the resulting fleet compositions for each of the mission scenarios.

Table 5.9: Resulting fleet composition test case 2. War scenario.

Run	Sub	LPD	LCF	M-Frigate	Patrol	JSS	CSS
1	10	2	4	8	4	1	1
2	7	2	4	5	4	1	1

Table 5.10 shows the fleet capabilities present in the generated fleet compositions for the war time scenario. The capability distribution follows the same trend as observed in test case 1.

Table 5.10: Fleet capabilities.

Capability	Landing	AAW	ASuW	ASW	Supply
Occurrence	3	12	22	8	2
	3	9	16	5	2

The resulting fleet compositions are within the expected range. The high mission density from a war time scenario requires more capabilities to be present within the fleet compositions. Since 5 out of the 7 vessel types are fixed results in the need for a high demand of new vessels, in this case submarines and M-frigates.

This hypothesis continues when looking at the fleet compositions generated for the peacetime scenario. For this scenario significantly less submarines and M-Frigates have been selected for the fleet.

Table 5.11: Resulting fleet composition test case 2. Peace scenario.

Run	Sub	LPD	LCF	M-Frigate	Patrol	JSS	CSS
1	0	2	4	2	4	1	1
2	3	2	4	4	4	1	1

Table 5.12 shows the total fleet capabilities of the fleet compositions generated for the peacetime scenario.

Table 5.12: Fleet capabilities.

Capability	Landing	AAW	ASuW	ASW	Supply
Occurrence	3	6	6	2	2
	3	8	11	4	2

In order to compare the different fleet compositions more information on the fleet performance is needed. Table 5.13 shows for each of the four fleet compositions the performance indicators. In this table the fitness value is the value resulting from the objective function and is used as an early performance indicator. Next, the success rate is the percentage of successful executed missions. So this is the number of successful missions divided by the total amount of missions in one simulation. Lastly, the number of vessels that are lost in battle over the simulation period is given.

Table 5.13: Performance comparison test case 2.

Scenario	Run	Fitness value	Success rate [%]	Vessels lost
War	1	0.89	56	2
	2	1.06	59	3
Peace	1	2.09	75	0
	2	2.14	83	0

Table 5.13 shows that the foundation of this fleet, the fixed vessel types, is more suitable for a peacetime scenario than for a wartime scenario. This first indication for this is the fitness value which is around 1 for the wartime optimized fleets where it is over 2 for the peacetime optimized fleets. This can also be concluded from the success rate and the attrition where the peacetime fleets perform better in both these aspects. This confirms the statement that the fleet size is the main parameter influencing the performance during a wartime scenario. The significantly larger amount of missions in the same time frame of a wartime scenario requires a larger fleet in order to maintain the same performance. This would also imply that the main reason for failing a mission in a wartime scenario for these fleets would be to fail meeting the mission requirements. Because the fleet is lacking in fleet size relatively fewer vessels are available for selection at any point in time, increasing the chance to fail meeting the mission requirements. Table 5.14 shows the distribution of reasons for mission failure for each of the four simulations.

Table 5.14: Distribution of reasons for mission failure test case 2.

Scenario	Run	Mission Requirements	Battle undecided	Battle lost	Expected loss
War	1	58	16	1	0
	2	53	17	1	0
Peace	1	7	6	0	0
	2	3	5	0	0

Table 5.14 shows that the hypothesis regarding the main reason for mission failure during a wartime scenario was correct. For both wartime optimized fleets over 70% of the failed missions were because the mission requirements could not be met.

2.1. Discussion on capability distribution

Throughout the first two test cases it became clear that even though the required mission capabilities follow a linear pattern, the fleet capabilities of the generated fleet compositions do not. The main reason for this lies in the definition of the different vessel types. Because the vessel types can contain more than one capability it becomes increasingly harder to perfectly match the fleet capabilities to the required mission capabilities. For example: the M-frigate contains the most amount of capabilities, AAW, ASuW, and ASW, but is also the only vessel type to carry the ASW capability (in the current definition). This means that when an additional M-frigate is selected by the model to enter the fleet composition in order to acquire the ASW capability, it also add AAW and ASuW to the fleet capabilities. Furthermore, ASuW is the most occurring capability in the current vessel type definition, it is carried by three different vessel types namely the submarine, M-frigate, and the patrol vessel. The combination of these two facts result in a consistent overcapacity of ASuW capability in the generated fleet compositions. This effect get more extreme when the fleet size grows. Figure 5.1 shows the fleet capabilities of all fleet compositions throughout test cases 1 and 2.

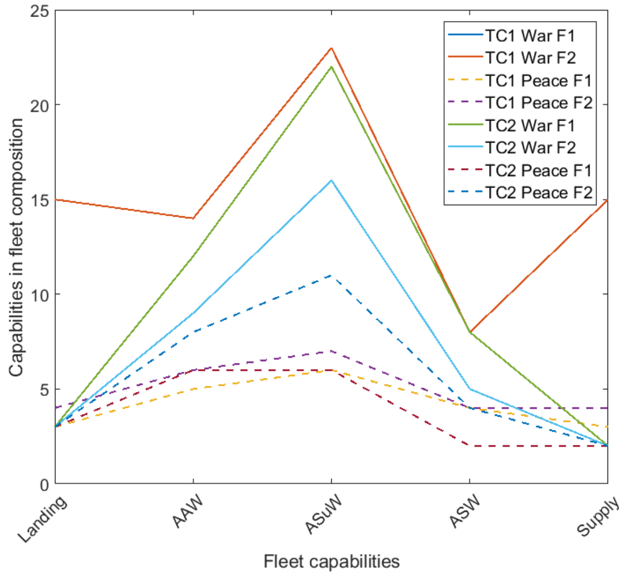


Figure 5.1: Fleet composition for $c = [1, 0, 5]$.

Figure 5.1 confirms the previously stated effect as the trend is similar throughout all different fleet compositions with the highest peak at the ASuW capability. The solid lines represent the composition in the wartime scenario and the dashed lines are for the peacetime fleet compositions. The figure shows that the smaller fleets associated with a peacetime scenario are less extreme in their capability distribution.

Having these extreme fluctuations and overcapacity of certain fleet capabilities is not ideal from a fleet design perspective. Given the fact that this originates from combining multiple capabilities on one vessel type suggests that the matching of fleet capabilities and required mission capabilities can be done more effectively by using more, smaller and specialized vessels.

3. Test case 3: Test fleet versatility.

The last test case will test the versatility of one single fleet by running it through multiple different mission scenarios. The fixed fleet composition that is used is: *[4, 2, 4, 2, 4, 1, 1]*. The fleet composition that is used for this test is arbitrary, however the reason for this specific composition is that it comes as close to the current fleet of the Royal Netherlands Navy as possible within the model specifications.

This fleet is run through a war scenario, peace scenario and an intermediate scenario. For the wartime and peacetime scenarios the same mission input is used as for test case 1 and 2. For the intermediate scenario a new set of missions is generated using the following input parameters.

Mission chance	=	6%	;	Every day has a 6% chance for a mission to occur.
Intel quality	=	random	;	The intel has a random offset to the original enemy fleet capabilities before each confrontation.
Simulation time	=	1460	;	The total simulation time is 1460 days (4 years).

The resulting missions scenario contains a total of 75 missions over a period of 4 years. The individual mission parameters can be found in tables A.14-A.17. The capability and location distribution is shown here.

Landing	:	22 times
Anti-Air-Warfare	:	28 times
Anti-Surface-Warfare	:	39 times
Anti-Sub-Warfare	:	27 times
Supply	:	31 times

Libya	:	13 times
Syria	:	18 times
Malta	:	16 times
Estonia	:	15 times
Germany	:	13 times

Each scenario is run two times in order to see the consistency of the results. As discussed in chapter 4 the priority of a naval fleet changes over the different scenarios. In wartime a fleet will mainly be focussed on mission successfulness rather than on the fleet size, where during peacetime the budget that a navy has for its fleet will generally be lower therefore the fleet size gets a higher priority than during wartime. To account for this in this test-case the same fleet is evaluated using the same objective function as presented in chapter 4 but with different weight-factors depending on the scenario. For the wartime and peacetime scenario the same weight-factors are used as in test-cases 1 and 2, respectively: [3, 1, 1] and [1, 2, 2]. So during wartime the mission successfulness is prioritized and during peacetime the fleet size and attrition are prioritized. In both cases the attrition priority is set to 1. The sensitivity study, presented 4.3, showed that this weight-factors is highly sensitive and does not need to be given a high value in order to prevent attrition. Since the intermediate scenario represents a volatile situation the classifies somewhere in between war and peace, the weight-factors that are used are also in between wartime and peacetime. Therefore equal weight-factors are chosen for this last scenario, [1, 1, 1].

The results of this test-case are presented in table 5.15.

Table 5.15: Results test case 3.

Scenario	Run	Fitness value	Success rate [%]	Vessels lost
War	1	-0.53	34	6
	2	0.11	41	2
Peace	1	1.36	55	2
	2	1.86	69	0
Intermediate	1	0.70	53	2
	2	0.94	65	2

Table 5.15 shows the two separate runs for each of the three different scenarios. The performance of the fleet is evaluated using three indicators. The first of which is the fitness value, this is the value that is generated by the objective function as explained in chapter 4. This value is used as first overall indication on the performance. The second indicator is the success rate, this is the percentage of missions that has been executed successfully over the full simulation scenario. Lastly, the amount of vessels that have been lost in battle is given.

From table 5.15 can be concluded that this specific fleet performs best in a peacetime scenario. This result is expected since this fleet is entirely designed during a long period of peace. The main parameter that causes the big difference in performance between the wartime scenario and the peacetime scenario is the fleet size. The same conclusion that is drawn in test-case 1 can also be made here, the higher mission density that comes with a wartime scenario requires a bigger fleet. This conclusion is strengthened by the fact that during run 1 of the wartime scenario 94 out of the total 113 failed missions were failed because the mission capability requirements could not be met. The same is true for the second run of the wartime scenario, where 84 out of the total 101 failed missions failed because the mission capability requirements could not be met. This information is also shown in table 5.16 along with the number of mission that failed for different reasons during each run. These different possibilities in which a mission can be considered as failed are first introduced in 3.2.

Table 5.16: Distribution of reasons for mission failure test case 3.

Scenario	Run	Mission requirements	Battle undecided	Battle lost	Expected loss
War	1	94	16	2	1
	2	84	13	1	3
Peace	1	14	8	1	0
	2	10	6	0	0
Intermediate	1	31	3	1	0
	2	18	7	1	0

Another thing to point out in table 5.15 is the influence of attrition on the performance of the fleet. This can be directly concluded from the difference in performance between the two runs in the peacetime scenario. During the first run two vessels are lost in battle early in the simulation, on day 281 out of the 1460 days. In this specific run the vessels that are lost are a submarine and the JSS. This means that for the rest of the 4 years of simulation the fleet needs to continue operating without these two vessels. At the end of the run this attrition caused the success rate to drop from 69% to 55%.

6
Conclusions & Discussion

When looking at the results from the test cases, shown in chapter 5, a conclusion can be drawn on whether the overall research questions can be answered. So can the model that has been created for this research actually provide insight into what makes a winning fleet? In order to show that the model proved to be capable of this the main conclusions that can be drawn from the test cases are discussed here.

- The first insight that the model provides is the influence of fleet size on the performance of the fleet. Or when put the other way around, how a denser mission scenario requires a larger fleet in order to stay operational. The reason behind this phenomenon is that, in order to be able to react to suddenly occurring missions, a wide variety of vessels needs to be available at all times. Given the fact that vessels can be unavailable due to maintenance or because they are executing a different mission, results in an increasing fleet size requirement when the mission density increases. This ultimately comes around to what it is that you want your fleet to be able to do?

- The model shows that different scenarios require different fleets. One reason for this is the mission density but a changing scenario also brings a change in priority. The very basic example of changing priorities used throughout this report is between a wartime scenario and a peacetime scenario. During a period of war the missions are plentiful and of high personal priority. This means in general that more money will be available for the naval fleet to be maintained and expanded. On the other hand, during a period of peace the direct need for a naval fleet is lower. This results in a smaller budget, which combined with the lower mission density leads to a smaller fleet. The model has proven that it is capable of providing insight in the way this change in priority affects the optimal fleet composition.

- The next conclusion that is drawn regards how the capability distribution over the different vessel types influences the fleet performance. Throughout the first two test cases it became clear that even though the required mission capabilities follow a linear pattern, sections 5.1 and 5.2, the fleet capabilities of the generated fleet compositions do not. The first hypothesis was that they would follow the same trend when the fleet composition was optimized. For example when more supply capabilities are required from the mission scenario, the optimized fleet would also contain relatively more supply capabilities. The reason this is not the case lies in the definition of the vessel types. Since multiple capabilities can be present on one vessel type adding one new vessel to the composition can result in unnecessarily adding extra capabilities to the fleet. Using the example vessel type definition this resulted in a significant peak in ASuW capabilities within the generated fleet compositions. From this conclusion a new hypothesis rises that by implementing more, smaller, specialized vessels this overcapacity of certain capabilities could be reduced creating a more effective fleet by matching the fleet capabilities more precisely with the required mission capabilities. However having a lot of smaller vessels is not cost-effective or necessarily practical. Having modular vessels would be the compromised solution between these two fleet design philosophies by taking the more mission specialized approach in a more cost-effective manner at the cost of response time. The higher response time is due to the need for reconfiguring the vessels before each mission when working with modular vessels. Because of this it would be interesting to take a deeper look into the addition of modular vessels in the Fleet Behaviour Model in the future.

- Lastly, the addition of attrition into the model by using Hughes' Salvo Model showed the impact of loosing a vessel on the performance over time. Optimizing the fleet capabilities too close on specific scenario requirements can lead to a highly vulnerable fleet composition where loosing one vessel can result in a drastic decrease in performance both through the loss of its capabilities and the added strain that is put on the rest of the fleet.

So, the results obtained with this relatively simple model with basic input parameters prove that this method is capable of providing insight that is useful in the early stages of designing a naval fleet. That being said there are some adaptations and additions that can be made in order to make the model more effective and productive. These will be discussed in Chapter 7.

7
Recommendations

After making and testing the Fleet Behaviour Model it became clear that the Fleet Behaviour Model could still use improvements in order to provide a better design and discussion tool. These improvements are shown here along with a short explanation on their significance. The first part will discuss ways in which the model can be expanded upon to provide more useful information. After this the second part will discuss a few ways in which the existing model can be further tested given the parameters and/or protocols that are already in place.

So, first the ways in which the model can be expanded upon are discussed here. The order also represents the priority.

Modular vessels and/or payload	:	As discussed in Chapter 6 including the possibility of modular vessels in the FBM could result in more effective fleets.
Crews/training	:	Because of the lack of time this has not been included in the current version of the model. However, because of the significant portion of a vessels' life cycle is spend on this activity it should be included. This could be implemented in a similar manner as the fleet maintenance.
Pre-emptive rescheduling of maintenance	:	Allowing the model to shift the maintenance schedule of a vessel to start earlier by planning ahead based on known upcoming missions could result in an improved availability and readiness at a time of need.
Variable vessel types	:	Giving the model freedom to design its own vessel types by combining capabilities could spark interesting new discussions.
More elaborate world simulation	:	Would allow for more specific mission types such as escort, intervention, and mine hunting missions. Furthermore, this would allow for a more elaborate interaction between different world parties and the influence that the actions have on one another.
Scouting	:	This addresses the situation where, under certain circumstances, it can be hard to find the enemy fleet or for them to find you. Applying this would introduce the ability to avoid combat.

The parameters of which their influence on the fleet performance can be tested in the future are:

Effective range	:	The influence of the effective range, including fuel, ammunition storage, and supplies, on the fleet performance.
Return after mission	:	Test whether staying at location after finishing a mission or return to Den Helder influences the fleet performance.
Offensive capability ratio selection	:	This regards the ratio between the offensive capabilities of the selected vessels and the expected opposition for a mission. Having a higher ratio gives a better chance of mission success at the cost of using more capabilities for that same mission.
Additional vessel selection	:	When selecting an additional vessel to overcome the opposition test the difference in fleet performance between choosing the closest available vessel or the closest vessel with useful mission capabilities.

A
Fixed mission scenarios

Table A.1: Missions over time during verification

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
5	30	Syria	0	1	1	0	1	3	1	1	10	0,75	1	22	1	1
6	6	Malta (HB)	0	0	0	1	0	3	1	1	18	0,75	1	38	1	1
10	9	Estonia	0	1	1	0	1	3	1	1	16	0,75	1	30	1	1
30	18	Malta (HB)	0	0	0	1	0	2	1	1	18	0,75	1	31	1	1
64	9	Germany (HB)	0	1	0	1	0	3	1	1	11	0,75	1	39	1	1
65	24	Libya	1	0	0	1	1	2	1	1	18	0,75	1	31	1	1
79	13	Germany (HB)	0	1	0	1	0	3	1	1	16	0,75	1	27	1	1
153	3	Libya	0	1	0	0	1	2	1	1	10	0,75	1	26	1	1
173	9	Germany (HB)	0	0	1	1	0	2	1	1	16	0,75	1	35	1	1
178	7	Malta (HB)	0	0	1	0	1	3	1	1	13	0,75	1	27	1	1
182	16	Germany (HB)	1	0	1	0	1	3	1	1	11	0,75	1	38	1	1
222	19	Libya	0	1	0	1	0	2	1	1	16	0,75	1	30	1	1
238	25	Libya	0	0	1	0	1	1	1	1	18	0,75	1	31	1	1
248	4	Germany (HB)	0	1	0	1	0	3	1	1	15	0,75	1	22	1	1
252	16	Germany (HB)	0	1	0	0	0	1	1	1	16	0,75	1	35	1	1
302	3	Germany (HB)	0	0	0	1	1	3	1	1	11	0,75	1	35	1	1
308	7	Lybia	1	1	0	0	0	3	1	1	14	0,75	1	35	1	1

Table A.2: Missions over time war scenario (part 1)

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
1	5	Libya	1	0	1	0	1	1	1	1	15	0.75	1	28	1	1
3	19	Libya	0	0	0	1	0	1	1	1	20	0.75	1	35	1	1
12	19	Estonia	1	1	1	0	0	2	1	1	12	0.75	1	28	1	1
23	9	Germany (HB)	1	0	0	0	0	2	1	1	17	0.75	1	21	1	1
30	10	Libya	0	0	0	0	1	2	1	1	18	0.75	1	32	1	1
42	28	Estonia	0	0	1	0	0	3	1	1	10	0.75	1	26	1	1
46	4	Germany (HB)	1	1	0	0	1	2	1	1	13	0.75	1	26	1	1
49	19	Estonia	1	0	0	0	1	2	1	1	10	0.75	1	40	1	1
65	26	Syria	0	1	1	1	0	2	1	1	16	0.75	1	27	1	1
83	17	Malta (HB)	0	0	0	0	1	1	1	1	17	0.75	1	32	1	1
85	19	Malta (HB)	0	1	0	0	1	2	1	1	10	0.75	1	29	1	1
86	11	Syria	0	0	1	0	0	3	1	1	14	0.75	1	28	1	1
97	22	Malta (HB)	1	1	0	1	0	1	1	1	14	0.75	1	32	1	1
103	12	Syria	0	1	0	0	0	2	1	1	19	0.75	1	28	1	1
112	6	Estonia	0	0	1	0	1	2	1	1	12	0.75	1	21	1	1
113	7	Malta (HB)	1	1	0	0	1	3	1	1	20	0.75	1	35	1	1
122	29	Syria	0	1	0	0	0	1	1	1	12	0.75	1	25	1	1
132	27	Malta (HB)	1	0	1	0	1	3	1	1	15	0.75	1	22	1	1
133	25	Estonia	1	0	1	0	0	2	1	1	18	0.75	1	35	1	1
136	2	Syria	1	0	1	0	0	1	1	1	11	0.75	1	31	1	1

Table A.3: Missions over time war scenario (part 2)

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
157	19	Germany (HB)	0	1	1	0	0	3	1	1	14	0.75	1	30	1	1
161	24	Syria	1	1	0	0	0	2	1	1	14	0.75	1	32	1	1
178	10	Libya	0	0	1	1	0	3	1	1	12	0.75	1	32	1	1
188	22	Libya	0	1	0	0	0	1	1	1	13	0.75	1	22	1	1
190	26	Germany (HB)	1	0	0	1	1	2	1	1	15	0.75	1	24	1	1
191	10	Libya	1	0	0	1	0	1	1	1	15	0.75	1	22	1	1
224	30	Libya	1	0	1	1	0	1	1	1	11	0.75	1	22	1	1
238	11	Libya	0	1	0	1	0	1	1	1	18	0.75	1	28	1	1
258	9	Germany (HB)	1	1	0	0	0	3	1	1	14	0.75	1	26	1	1
261	26	Estonia	0	0	0	0	1	3	1	1	16	0.75	1	28	1	1
262	24	Germany (HB)	0	0	0	0	1	3	1	1	14	0.75	1	35	1	1
270	2	Syria	0	0	1	1	1	2	1	1	15	0.75	1	31	1	1
274	1	Germany (HB)	0	1	1	1	0	1	1	1	18	0.75	1	31	1	1
282	2	Libya	1	1	0	0	0	3	1	1	20	0.75	1	23	1	1
290	29	Syria	0	1	0	1	1	1	1	1	13	0.75	1	33	1	1
306	29	Germany (HB)	0	0	0	0	1	3	1	1	15	0.75	1	32	1	1
313	23	Libya	0	1	1	1	0	1	1	1	12	0.75	1	32	1	1
316	27	Libya	0	1	0	0	1	1	1	1	20	0.75	1	39	1	1
324	9	Estonia	0	1	1	0	1	1	1	1	11	0.75	1	23	1	1
330	23	Germany (HB)	0	0	1	0	1	1	1	1	16	0.75	1	28	1	1

Table A.4: Missions over time war scenario (part 3)

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
354	12	Malta (HB)	0	0	0	0	1	1	1	1	12	0.75	1	27	1	1
360	1	Syria	0	0	1	1	0	2	1	1	18	0.75	1	33	1	1
363	12	Germany (HB)	0	1	0	1	1	1	1	1	14	0.75	1	35	1	1
378	27	Malta (HB)	0	0	0	0	1	3	1	1	19	0.75	1	37	1	1
382	25	Syria	0	0	0	1	0	1	1	1	14	0.75	1	23	1	1
391	9	Libya	1	0	0	1	0	2	1	1	15	0.75	1	21	1	1
393	11	Libya	0	0	1	1	0	2	1	1	14	0.75	1	36	1	1
412	19	Malta (HB)	0	1	0	1	1	1	1	1	10	0.75	1	34	1	1
420	4	Libya	1	1	0	1	0	2	1	1	18	0.75	1	35	1	1
450	25	Syria	1	0	0	1	1	3	1	1	14	0.75	1	33	1	1
460	9	Syria	0	1	1	0	1	3	1	1	13	0.75	1	34	1	1
464	8	Estonia	1	1	0	1	0	1	1	1	12	0.75	1	38	1	1
471	29	Malta (HB)	0	1	0	1	1	2	1	1	12	0.75	1	36	1	1
486	1	Syria	0	1	0	0	1	2	1	1	10	0.75	1	35	1	1
506	26	Libya	0	0	1	0	0	2	1	1	16	0.75	1	30	1	1
521	21	Syria	1	0	1	0	0	1	1	1	17	0.75	1	37	1	1
572	29	Malta (HB)	0	0	0	1	1	2	1	1	12	0.75	1	25	1	1
573	30	Estonia	1	0	0	1	0	3	1	1	19	0.75	1	22	1	1
575	29	Libya	0	0	0	1	0	1	1	1	16	0.75	1	32	1	1
594	17	Estonia	0	0	1	1	1	1	1	1	18	0.75	1	37	1	1

Table A.5: Missions over time war scenario (part 4)

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
596	9	Syria	0	0	1	0	1	2	1	1	12	0.75	1	27	1	1
632	8	Libya	1	1	0	1	0	3	1	1	15	0.75	1	30	1	1
636	19	Estonia	0	0	1	0	0	2	1	1	10	0.75	1	25	1	1
638	18	Estonia	1	0	1	1	0	1	1	1	17	0.75	1	22	1	1
644	11	Syria	1	0	0	1	1	2	1	1	10	0.75	1	37	1	1
651	12	Germany (HB)	0	0	0	0	1	1	1	1	14	0.75	1	37	1	1
673	4	Estonia	0	1	0	1	1	1	1	1	19	0.75	1	30	1	1
674	28	Libya	1	0	0	0	1	2	1	1	13	0.75	1	26	1	1
675	5	Malta (HB)	0	1	0	1	0	3	1	1	13	0.75	1	36	1	1
683	16	Libya	0	1	1	0	0	1	1	1	16	0.75	1	33	1	1
691	14	Estonia	1	0	0	0	1	3	1	1	11	0.75	1	22	1	1
694	29	Estonia	0	0	1	0	0	1	1	1	12	0.75	1	31	1	1
695	18	Libya	1	1	1	0	0	3	1	1	20	0.75	1	32	1	1
697	23	Estonia	0	0	0	0	1	1	1	1	11	0.75	1	21	1	1
710	29	Syria	1	1	1	0	0	2	1	1	18	0.75	1	37	1	1
718	5	Syria	0	0	1	0	0	1	1	1	15	0.75	1	32	1	1
721	6	Estonia	0	1	1	0	1	2	1	1	11	0.75	1	26	1	1
728	27	Germany (HB)	0	0	1	0	0	1	1	1	19	0.75	1	29	1	1
746	2	Syria	0	1	0	1	0	1	1	1	20	0.75	1	26	1	1
758	16	Germany (HB)	0	0	0	1	0	2	1	1	18	0.75	1	21	1	1

Table A.6: Missions over time war scenario (part 5)

			Capability requirements					Enemy fleet								
Day	ToL	Location	Landing	AAW	ASuW	ASW	Supply	B	b1	b2	Off_AmmoB	Hb	b3	Def_AmmoB	sigmaB	deltaB
773	3	Germany (HB)	1	0	1	0	0	1	1	1	17	0.75	1	27	1	1
774	20	Libya	0	1	1	0	0	3	1	1	19	0.75	1	22	1	1
787	29	Syria	1	0	0	0	1	2	1	1	17	0.75	1	23	1	1
791	16	Libya	1	0	0	0	0	1	1	1	17	0.75	1	24	1	1
794	14	Germany (HB)	0	1	0	0	0	3	1	1	15	0.75	1	30	1	1
796	20	Syria	1	1	1	0	0	1	1	1	16	0.75	1	33	1	1
797	9	Estonia	0	1	0	1	0	2	1	1	13	0.75	1	25	1	1
801	7	Germany (HB)	0	1	0	0	0	3	1	1	17	0.75	1	25	1	1
821	3	Malta (HB)	0	1	1	1	0	3	1	1	11	0.75	1	23	1	1
834	21	Estonia	1	0	0	0	1	3	1	1	15	0.75	1	29	1	1
851	19	Estonia	1	1	0	0	1	3	1	1	20	0.75	1	36	1	1
855	12	Syria	0	0	0	1	0	3	1	1	14	0.75	1	23	1	1
859	23	Estonia	0	0	1	0	1	1	1	1	13	0.75	1	35	1	1
861	7	Germany (HB)	1	0	0	0	0	1	1	1	13	0.75	1	33	1	1
875	13	Germany (HB)	0	1	0	0	1	1	1	1	12	0.75	1	40	1	1
883	10	Estonia	0	0	1	0	0	2	1	1	16	0.75	1	38	1	1
885	12	Estonia	0	1	0	1	0	3	1	1	11	0.75	1	24	1	1
889	26	Estonia	0	0	0	0	1	1	1	1	13	0.75	1	20	1	1
901	16	Libya	0	0	0	1	1	1	1	1	18	0.75	1	39	1	1
917	9	Germany (HB)	0	0	0	1	1	2	1	1	20	0.75	1	27	1	1

Table A.7: Missions over time war scenario (part 6)

			Capability requirements					Enemy fleet								
Day	ToL	Location	Landing	AAW	ASuW	ASW	Supply	B	b1	b2	Off_AmmoB	Hb	b3	Def_AmmoB	sigmaB	deltaB
929	26	Libya	1	0	1	0	0	3	1	1	18	0.75	1	22	1	1
931	26	Estonia	0	1	1	0	1	2	1	1	10	0.75	1	37	1	1
932	5	Syria	1	1	0	0	1	1	1	1	14	0.75	1	29	1	1
949	26	Malta (HB)	0	1	1	1	0	1	1	1	13	0.75	1	39	1	1
952	22	Libya	0	0	0	1	0	1	1	1	15	0.75	1	38	1	1
953	12	Estonia	1	1	1	0	0	3	1	1	17	0.75	1	39	1	1
955	3	Syria	1	0	1	0	0	2	1	1	11	0.75	1	34	1	1
975	14	Estonia	0	0	0	1	0	3	1	1	19	0.75	1	30	1	1
980	16	Syria	0	1	1	1	0	2	1	1	10	0.75	1	25	1	1
992	8	Germany (HB)	0	1	0	1	0	2	1	1	17	0.75	1	32	1	1
994	16	Syria	0	0	0	1	0	2	1	1	16	0.75	1	25	1	1
1003	20	Germany (HB)	0	1	1	0	0	3	1	1	11	0.75	1	37	1	1
1012	4	Syria	0	0	0	1	0	1	1	1	16	0.75	1	39	1	1
1023	23	Syria	1	0	1	0	1	3	1	1	14	0.75	1	37	1	1
1028	24	Germany (HB)	0	0	0	1	0	2	1	1	20	0.75	1	28	1	1
1040	6	Estonia	1	1	0	0	1	2	1	1	20	0.75	1	34	1	1
1041	13	Estonia	0	0	1	1	1	1	1	1	13	0.75	1	23	1	1
1054	29	Libya	0	1	1	0	0	2	1	1	16	0.75	1	27	1	1
1057	17	Libya	1	0	1	1	0	2	1	1	14	0.75	1	33	1	1
1058	6	Libya	1	0	0	0	1	2	1	1	18	0.75	1	28	1	1

Table A.8: Missions over time war scenario (part 7)

			Capability requirements					Enemy fleet								
Day	ToL	Location	Landing	AAW	ASuW	ASW	Supply	B	b1	b2	Off_AmmoB	Hb	b3	Def_AmmoB	sigmaB	deltaB
1075	21	Libya	1	1	0	0	0	1	1	1	13	0.75	1	32	1	1
1076	25	Malta (HB)	0	0	0	1	0	1	1	1	10	0.75	1	36	1	1
1077	2	Malta (HB)	0	1	0	1	1	1	1	1	17	0.75	1	31	1	1
1078	2	Syria	0	0	0	1	1	2	1	1	12	0.75	1	23	1	1
1091	27	Germany (HB)	0	0	1	1	0	1	1	1	10	0.75	1	39	1	1
1122	20	Malta (HB)	0	0	0	1	0	3	1	1	17	0.75	1	24	1	1
1132	28	Syria	0	1	1	0	0	1	1	1	12	0.75	1	39	1	1
1139	10	Estonia	0	0	0	1	1	2	1	1	19	0.75	1	22	1	1
1158	28	Estonia	0	1	0	1	1	2	1	1	16	0.75	1	20	1	1
1160	30	Germany (HB)	1	1	0	1	0	3	1	1	15	0.75	1	21	1	1
1166	16	Libya	1	1	0	0	1	1	1	1	12	0.75	1	24	1	1
1168	25	Syria	0	1	0	0	0	1	1	1	13	0.75	1	28	1	1
1174	9	Germany (HB)	1	0	1	0	1	3	1	1	10	0.75	1	34	1	1
1180	26	Syria	0	0	1	1	1	1	1	1	18	0.75	1	30	1	1
1184	13	Syria	1	0	0	0	1	1	1	1	15	0.75	1	20	1	1
1185	24	Germany (HB)	1	0	0	0	1	1	1	1	19	0.75	1	39	1	1
1187	3	Germany (HB)	0	1	1	0	0	1	1	1	17	0.75	1	31	1	1
1188	19	Malta (HB)	0	0	1	1	0	2	1	1	13	0.75	1	23	1	1
1205	27	Libya	0	0	0	1	1	1	1	1	13	0.75	1	36	1	1
1209	1	Libya	0	0	1	0	0	2	1	1	12	0.75	1	35	1	1

Table A.9: Missions over time war scenario (part 8)

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
1211	18	Syria	0	0	0	0	1	2	1	1	10	0.75	1	22	1	1
1222	26	Germany (HB)	1	0	1	0	0	3	1	1	15	0.75	1	36	1	1
1237	26	Malta (HB)	0	0	0	1	0	1	1	1	16	0.75	1	32	1	1
1240	7	Estonia	1	1	0	0	0	2	1	1	17	0.75	1	25	1	1
1241	12	Libya	0	1	1	0	1	3	1	1	16	0.75	1	31	1	1
1245	7	Germany (HB)	1	0	0	0	0	3	1	1	14	0.75	1	25	1	1
1249	30	Syria	0	0	0	1	0	2	1	1	16	0.75	1	38	1	1
1252	21	Syria	0	0	1	1	1	1	1	1	15	0.75	1	22	1	1
1256	27	Malta (HB)	1	0	0	1	1	2	1	1	19	0.75	1	30	1	1
1260	18	Libya	0	0	1	0	0	1	1	1	10	0.75	1	37	1	1
1276	30	Libya	1	0	0	0	0	3	1	1	15	0.75	1	22	1	1
1312	1	Malta (HB)	1	0	1	1	0	1	1	1	16	0.75	1	28	1	1
1318	27	Estonia	0	0	0	1	0	1	1	1	20	0.75	1	25	1	1
1319	24	Syria	1	0	0	0	0	3	1	1	19	0.75	1	30	1	1
1327	12	Libya	0	1	1	1	0	3	1	1	14	0.75	1	21	1	1
1334	30	Malta (HB)	0	1	0	1	0	2	1	1	14	0.75	1	22	1	1
1349	2	Estonia	1	0	0	0	0	1	1	1	15	0.75	1	21	1	1
1351	1	Syria	1	0	1	1	0	1	1	1	14	0.75	1	23	1	1
1368	7	Germany (HB)	0	1	0	0	0	2	1	1	13	0.75	1	37	1	1
1373	6	Malta (HB)	0	1	1	0	1	1	1	1	16	0.75	1	21	1	1

Table A.10: Missions over time war scenario (part 9)

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
1384	14	Libya	0	1	0	1	0	3	1	1	11	0.75	1	29	1	1
1392	17	Libya	1	1	0	0	1	3	1	1	16	0.75	1	28	1	1
1398	19	Germany (HB)	0	1	0	0	0	1	1	1	18	0.75	1	20	1	1
1402	5	Libya	0	1	1	1	0	3	1	1	18	0.75	1	34	1	1
1409	8	Syria	1	1	1	0	0	1	1	1	12	0.75	1	30	1	1
1412	1	Estonia	1	0	0	1	1	3	1	1	17	0.75	1	26	1	1
1413	5	Libya	0	0	0	1	0	1	1	1	19	0.75	1	37	1	1
1422	13	Libya	1	1	0	0	1	1	1	1	13	0.75	1	24	1	1
1429	9	Libya	0	0	0	1	1	3	1	1	11	0.75	1	26	1	1
1434	12	Estonia	0	0	0	1	1	1	1	1	14	0.75	1	40	1	1
1440	29	Syria	0	0	1	0	0	3	1	1	11	0.75	1	30	1	1
1450	12	Malta (HB)	0	1	1	0	1	1	1	1	13	0.75	1	24	1	1

Table A.11: Missions over time peace scenario (part 1)

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
5	9	Syria	0	0	0	1	0	2	1	1	12	0,75	1	23	1	1
15	15	Libya	0	1	0	0	0	3	1	1	18	0,75	1	35	1	1
43	27	Germany	0	0	1	0	0	3	1	1	10	0,75	1	39	1	1
55	6	Germany	0	1	1	1	0	2	1	1	19	0,75	1	38	1	1
77	12	Malta	1	0	0	1	1	2	1	1	19	0,75	1	30	1	1
99	30	Germany	1	0	0	0	0	1	1	1	12	0,75	1	31	1	1
113	23	Syria	0	1	1	0	1	2	1	1	19	0,75	1	20	1	1
132	2	Estonia	0	0	0	1	0	1	1	1	15	0,75	1	37	1	1
231	26	Germany	0	1	0	0	0	2	1	1	18	0,75	1	26	1	1
259	11	Estonia	0	1	0	1	0	1	1	1	18	0,75	1	27	1	1
279	16	Germany	1	0	1	0	0	0	1	1	13	0,75	1	37	1	1
281	11	Syria	1	0	0	0	1	2	1	1	10	0,75	1	28	1	1
302	8	Malta	1	0	0	0	1	0	1	1	15	0,75	1	30	1	1
339	15	Libya	0	1	0	0	0	2	1	1	18	0,75	1	25	1	1
347	5	Malta	1	0	1	0	0	2	1	1	10	0,75	1	32	1	1
376	3	Germany	1	0	0	0	1	2	1	1	17	0,75	1	31	1	1
389	8	Malta	0	0	0	1	0	0	1	1	10	0,75	1	24	1	1
392	19	Germany	0	1	1	1	0	2	1	1	15	0,75	1	26	1	1
466	10	Estonia	0	1	0	0	0	2	1	1	18	0,75	1	25	1	1
467	26	Germany	0	0	1	0	1	2	1	1	14	0,75	1	21	1	1

Table A.12: Missions over time peace scenario (part 2)

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
484	2	Estonia	0	0	1	1	0	2	1	1	16	0,75	1	36	1	1
494	15	Syria	0	1	1	0	1	0	1	1	11	0,75	1	29	1	1
535	25	Estonia	1	1	0	0	1	2	1	1	17	0,75	1	25	1	1
542	12	Syria	1	1	0	1	0	0	1	1	18	0,75	1	24	1	1
593	13	Germany	0	0	1	0	1	2	1	1	17	0,75	1	28	1	1
617	25	Syria	1	0	0	0	1	3	1	1	12	0,75	1	25	1	1
658	17	Germany	0	0	1	0	1	1	1	1	11	0,75	1	29	1	1
666	24	Libya	0	1	1	0	1	3	1	1	17	0,75	1	37	1	1
673	17	Syria	0	1	0	0	1	1	1	1	19	0,75	1	22	1	1
682	25	Estonia	0	1	1	0	1	0	1	1	16	0,75	1	32	1	1
703	1	Syria	1	0	1	0	0	3	1	1	17	0,75	1	30	1	1
761	11	Syria	0	1	0	0	0	2	1	1	10	0,75	1	22	1	1
818	29	Estonia	1	1	0	0	1	3	1	1	18	0,75	1	26	1	1
835	23	Libya	0	0	0	0	1	1	1	1	16	0,75	1	32	1	1
908	27	Libya	0	0	1	0	1	0	1	1	17	0,75	1	30	1	1
942	11	Estonia	1	0	0	1	0	3	1	1	16	0,75	1	27	1	1
962	28	Estonia	0	1	0	0	0	2	1	1	10	0,75	1	28	1	1
1028	8	Syria	0	1	1	0	1	2	1	1	17	0,75	1	32	1	1
1038	6	Malta	0	0	1	0	0	2	1	1	19	0,75	1	31	1	1
1045	11	Syria	0	0	1	1	1	2	1	1	19	0,75	1	22	1	1

Table A.13: Missions over time peace scenario (part 3)

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
1076	6	Libya	1	0	0	1	0	2	1	1	12	0,75	1	36	1	1
1095	20	Malta	0	0	0	1	1	0	1	1	18	0,75	1	39	1	1
1162	9	Syria	1	0	0	1	0	0	1	1	11	0,75	1	23	1	1
1175	17	Libya	1	0	1	1	0	0	1	1	11	0,75	1	23	1	1
1177	4	Syria	0	0	0	1	0	2	1	1	20	0,75	1	37	1	1
1192	13	Estonia	0	1	0	0	0	1	1	1	13	0,75	1	30	1	1
1213	19	Germany	1	0	1	0	1	0	1	1	16	0,75	1	29	1	1
1284	19	Libya	0	0	0	1	0	1	1	1	20	0,75	1	35	1	1
1321	30	Malta	0	1	1	0	0	0	1	1	19	0,75	1	26	1	1
1343	8	Malta	0	0	1	1	1	1	1	1	10	0,75	1	29	1	1
1358	26	Syria	0	0	1	1	1	3	1	1	15	0,75	1	27	1	1

Table A.14: Missions over time intermediate scenario (part 1)

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
18	3	Libya	0	1	0	1	0	3	1	1	12	0,75	1	33	1	1
34	6	Libya	0	1	1	0	0	1	1	1	17	0,75	1	36	1	1
61	22	Malta	1	0	0	1	1	2	1	1	13	0,75	1	39	1	1
63	27	Malta	0	0	0	1	1	1	1	1	16	0,75	1	30	1	1
115	8	Syria	0	0	0	0	1	2	1	1	14	0,75	1	29	1	1
133	16	Malta	0	0	1	0	1	2	1	1	11	0,75	1	23	1	1
184	18	Estonia	1	0	1	0	1	1	1	1	18	0,75	1	20	1	1
185	5	Malta	0	1	0	1	1	0	1	1	10	0,75	1	29	1	1
186	20	Libya	1	1	0	1	0	2	1	1	18	0,75	1	38	1	1
226	5	Libya	0	1	0	0	0	1	1	1	10	0,75	1	24	1	1
237	7	Estonia	1	0	1	0	1	3	1	1	14	0,75	1	39	1	1
250	17	Libya	1	0	1	0	0	2	1	1	17	0,75	1	24	1	1
261	18	Estonia	0	1	0	1	0	1	1	1	17	0,75	1	33	1	1
274	18	Malta	1	0	1	0	1	2	1	1	13	0,75	1	39	1	1
281	12	Libya	1	1	0	1	0	3	1	1	13	0,75	1	32	1	1
287	26	Syria	0	1	0	1	0	2	1	1	18	0,75	1	25	1	1
357	10	Germany	0	0	1	0	1	0	1	1	18	0,75	1	29	1	1
382	30	Malta	0	0	1	0	0	3	1	1	18	0,75	1	31	1	1
398	15	Libya	1	0	1	1	0	1	1	1	16	0,75	1	31	1	1
436	4	Malta	0	1	0	0	0	3	1	1	16	0,75	1	20	1	1

Table A.15: Missions over time intermediate scenario (part 2)

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
442	29	Germany	0	0	0	0	1	0	1	1	11	0,75	1	32	1	1
466	26	Malta	1	1	0	0	1	2	1	1	11	0,75	1	28	1	1
499	12	Malta	1	0	1	1	0	3	1	1	14	0,75	1	21	1	1
529	3	Syria	0	0	1	1	1	2	1	1	16	0,75	1	37	1	1
546	11	Syria	0	0	1	1	0	1	1	1	17	0,75	1	36	1	1
549	11	Germany	0	0	1	0	0	2	1	1	12	0,75	1	37	1	1
559	18	Syria	0	1	1	1	0	2	1	1	18	0,75	1	25	1	1
637	16	Estonia	0	1	1	0	1	2	1	1	16	0,75	1	39	1	1
656	18	Estonia	0	0	1	0	0	1	1	1	13	0,75	1	33	1	1
657	2	Germany	0	1	0	0	1	2	1	1	14	0,75	1	22	1	1
663	25	Libya	1	0	1	0	0	2	1	1	15	0,75	1	24	1	1
669	20	Estonia	0	0	1	0	0	1	1	1	12	0,75	1	39	1	1
670	29	Estonia	0	0	1	0	0	2	1	1	15	0,75	1	34	1	1
672	24	Syria	0	0	0	1	1	2	1	1	18	0,75	1	34	1	1
714	5	Germany	1	0	0	0	0	1	1	1	20	0,75	1	27	1	1
720	2	Libya	0	0	1	0	1	2	1	1	10	0,75	1	37	1	1
743	9	Malta	0	1	0	0	1	3	1	1	20	0,75	1	22	1	1
790	26	Libya	0	0	0	0	1	1	1	1	16	0,75	1	37	1	1
804	23	Syria	0	0	1	0	0	1	1	1	18	0,75	1	27	1	1
811	10	Estonia	0	0	1	1	0	3	1	1	15	0,75	1	31	1	1

Table A.16: Missions over time intermediate scenario (part 3)

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
818	10	Syria	0	0	0	1	1	2	1	1	17	0,75	1	29	1	1
828	8	Malta	1	0	1	1	0	2	1	1	17	0,75	1	24	1	1
853	22	Libya	0	0	1	0	0	2	1	1	18	0,75	1	28	1	1
878	17	Syria	0	0	1	0	0	0	1	1	11	0,75	1	25	1	1
920	29	Estonia	0	1	1	1	0	2	1	1	12	0,75	1	31	1	1
922	20	Estonia	1	1	0	1	0	3	1	1	12	0,75	1	20	1	1
931	24	Estonia	0	0	0	1	1	3	1	1	18	0,75	1	21	1	1
932	3	Germany	0	1	1	0	1	1	1	1	17	0,75	1	30	1	1
933	25	Estonia	1	0	0	0	0	3	1	1	19	0,75	1	30	1	1
946	21	Syria	1	0	0	0	0	1	1	1	13	0,75	1	27	1	1
962	1	Syria	0	1	0	1	0	1	1	1	20	0,75	1	35	1	1
983	4	Germany	0	0	0	1	0	0	1	1	15	0,75	1	31	1	1
1013	12	Syria	0	1	0	0	1	1	1	1	17	0,75	1	27	1	1
1026	3	Syria	0	0	1	0	0	2	1	1	15	0,75	1	27	1	1
1037	20	Germany	0	1	0	1	0	0	1	1	11	0,75	1	35	1	1
1077	1	Estonia	1	0	0	1	1	2	1	1	20	0,75	1	30	1	1
1101	13	Libya	0	1	1	0	0	2	1	1	16	0,75	1	24	1	1
1104	8	Germany	0	0	1	0	0	0	1	1	20	0,75	1	40	1	1
1107	9	Germany	0	1	0	1	0	1	1	1	19	0,75	1	34	1	1
1151	2	Estonia	1	0	1	1	0	2	1	1	11	0,75	1	28	1	1

Table A.17: Missions over time intermediate scenario (part 4)

			Capability requirements					Enemy fleet								
Day	**ToL**	**Location**	**Landing**	**AAW**	**ASuW**	**ASW**	**Supply**	**B**	**b1**	**b2**	**Off_AmmoB**	**Hb**	**b3**	**Def_AmmoB**	**sigmaB**	**deltaB**
1172	19	Malta	0	0	0	0	1	2	1	1	17	0,75	1	39	1	1
1200	9	Syria	0	1	1	0	0	0	1	1	11	0,75	1	38	1	1
1209	21	Malta	1	0	1	0	0	3	1	1	16	0,75	1	24	1	1
1212	23	Syria	0	0	1	1	1	2	1	1	10	0,75	1	39	1	1
1233	26	Germany	0	1	0	0	0	1	1	1	14	0,75	1	26	1	1
1241	8	Malta	0	0	0	0	1	1	1	1	17	0,75	1	33	1	1
1247	15	Syria	0	0	1	0	1	2	1	1	11	0,75	1	27	1	1
1257	16	Estonia	0	0	1	0	0	2	1	1	19	0,75	1	22	1	1
1271	26	Malta	0	0	0	0	1	2	1	1	20	0,75	1	23	1	1
1274	10	Malta	0	0	0	0	1	2	1	1	18	0,75	1	30	1	1
1285	30	Germany	0	1	1	0	1	2	1	1	15	0,75	1	31	1	1
1288	28	Syria	1	1	0	0	1	1	1	1	10	0,75	1	29	1	1
1329	7	Syria	0	1	0	0	0	2	1	1	15	0,75	1	28	1	1
1331	9	Libya	1	1	1	0	0	1	1	1	18	0,75	1	23	1	1
1437	26	Germany	1	0	1	0	0	1	1	1	19	0,75	1	26	1	1

B

Test case mission results

Table B.1: Mission results summary. Test case 1, war scenario. Composition: [7, 7, 6, 8, 8, 8, 7] part 1

Mission day	Selected vessels	Mission result
1	Submarine, LPD, LPD, Patrol, Patrol, CSS	Success
3	Submarine, M-Frigate, M-Frigate, M-Frigate	Success
12	LPD, LPD, LCF, LCF, Patrol, Patrol	Success
23	Submarine, Submarine, LPD, LPD	Success
30	Submarine, Submarine, CSS	Success
42	LPD, LPD, LCF, Patrol, Patrol	Success
46	LPD, LPD, LCF, CSS, CSS	Success
49	Submarine, JSS, CSS	Success
65	Submarine, M-Frigate	Success
83	Submarine, CSS	Failed: Battle undecided.
85	LCF, LCF, LCF, M-Frigate, JSS	Success
86	Submarine, LPD, M-Frigate, Patrol, Patrol	Success
97	M-Frigate, M-Frigate, JSS	Success
103	Submarine, Submarine, LCF	Failed: Battle undecided.
112	Submarine, LPD, Patrol, CSS	Success
113	Submarine, LCF, LCF, LCF, JSS, CSS	Success
122	Submarine, M-Frigate	Failed: Battle undecided.
132	Submarine, LCF, JSS, JSS, CSS	Success
133	Submarine, LPD, LPD, Patrol	Success
136	LPD, Patrol	Failed: Battle undecided.
157	Submarine, LPD, M-Frigate, CSS	Success
161	Submarine, LCF, LCF, JSS, JSS	Success
178	Submarine, M-Frigate, CSS	Failed: Battle lost.
188	Submarine, M-Frigate	Failed: Battle undecided.
190	LPD, M-Frigate, CSS, CSS	Success
191	LPD, LPD, M-Frigate	Success
224	Submarine, LPD, LPD, M-Frigate, Patrol	Success
238	M-Frigate	Success
258	LPD, LPD, LCF, M-Frigate	Success
261	Submarine, LCF, Patrol, CSS, CSS, CSS	Success
262	Submarine, M-Frigate, Patrol, JSS, JSS, JSS, JSS	Success
270	Submarine, Submarine, Submarine, M-Frigate, Patrol, JSS	Success
274	LCF, M-Frigate	Failed: Battle undecided.
282	LPD, LPD, LCF, M-Frigate	Success
290	LCF, LCF, LCF, LCF, M-Frigate, M-Frigate, M-Frigate, JSS	Success
306	Submarine, LPD, LPD, JSS, JSS	Success
313	Submarine, Submarine, Submarine, M-Frigate	Success
316	M-Frigate, M-Frigate, CSS	Success
324	Submarine, M-Frigate, Patrol, CSS, CSS	Success
330	Submarine, Patrol, JSS	Success
354	Submarine, CSS	Success
360	LCF, M-Frigate	Success
363	LCF, M-Frigate, CSS, CSS, CSS	Success
378	Submarine, M-Frigate, M-Frigate, CSS	Success
382	LCF, M-Frigate	Success
391	LPD, LPD, LPD, LPD, LCF, M-Frigate	Success
393	-	Failed: Can not meet mission requirements
412	M-Frigate, M-Frigate, CSS	Success
420	LPD, LPD, LPD, LPD, LCF, M-Frigate	Success
450	LPD, LPD, LPD, LPD, LPD, LCF, M-Frigate, M-Frigate, M-Frigate, M-Frigate, CSS	Success
460	Submarine, Submarine, LCF, LCF, Patrol, CSS	Success
464	LPD, LCF, M-Frigate	Success
471	LCF, M-Frigate, CSS	Failed: Battle undecided.
486	Submarine, LCF, LCF, LCF, CSS, CSS	Success
506	Submarine, Submarine, LPD, Patrol	Success
521	LPD, LPD, M-Frigate	Success
572	LCF, M-Frigate, CSS, CSS, CSS	Success

Table B.2: Mission results summary. Test case 1, war scenario. Composition: [7, 7, 6, 8, 8, 8, 7] part 2

Mission day	Selected vessels	Mission result
573	Submarine, LPD, LPD, M-Frigate	Success
575	Submarine, M-Frigate	Success
594	Submarine, M-Frigate, CSS	Success
596	LPD, Patrol, JSS	Success
632	Submarine, LPD, LCF, LCF, M-Frigate, M-Frigate	Success
636	Submarine, Submarine, LPD	Success
638	LPD, M-Frigate, M-Frigate	Success
644	LPD, M-Frigate, JSS	Success
651	Submarine, CSS, CSS, CSS	Success
673	M-Frigate, CSS	Success
674	Submarine, LPD, JSS	Failed: Battle undecided.
675	LCF, LCF, M-Frigate	Success
683	LCF, LCF, M-Frigate	Success
691	Submarine, Submarine, LPD, LPD, CSS	Success
694	Submarine, M-Frigate	Failed: Battle undecided.
695	Submarine, Submarine, LPD, LPD, LPD, LCF, LCF, LCF, LCF, Patrol	Success
697	CSS, CSS	Success
710	LPD, M-Frigate, M-Frigate	Success
718	Submarine, JSS	Success
721	Submarine, Submarine, M-Frigate, Patrol, CSS, CSS, CSS	Success
728	Submarine, JSS	Success
746	LCF, LCF, LCF, M-Frigate	Success
758	LPD, M-Frigate, JSS	Failed: Battle undecided.
773	Submarine, JSS	Failed: Battle undecided.
774	Submarine, LPD, LPD, LCF, Patrol	Success
787	LCF, JSS	Failed: Battle lost.
791	LPD, LCF	Failed: Battle undecided.
794	Submarine, LPD, M-Frigate, M-Frigate	Success
796	M-Frigate, M-Frigate, M-Frigate, JSS	Success
797	Submarine, M-Frigate	Success
801	LCF, JSS, JSS, JSS	Failed: Battle undecided.
821	Submarine, Submarine, Submarine, LPD, LCF, LCF, LCF, M-Frigate, Patrol	Success
834	Submarine, Submarine, JSS, CSS, CSS	Success
851	LPD, M-Frigate, JSS	Success
855	M-Frigate, M-Frigate, M-Frigate, JSS	Success
859	Submarine, Submarine, CSS, CSS	Success
861	LPD, LPD, LCF	Success
875	LCF, CSS	Success
883	Submarine, Submarine, LPD	Success
885	M-Frigate, JSS, JSS	Success
889	CSS, CSS	Failed: Battle undecided.
901	M-Frigate, JSS	Success
917	LPD, M-Frigate, CSS, CSS, CSS	Success
929	Submarine, Submarine, M-Frigate, JSS	Failed: Battle undecided.
931	Submarine, M-Frigate, CSS, CSS, CSS	Success
932	LPD, LPD, LCF, LCF, JSS	Success
949	LCF, LCF, M-Frigate, Patrol	Success
952	LPD, M-Frigate	Success
953	LPD, LCF, Patrol, JSS	Success
955	LPD, M-Frigate, JSS, JSS, JSS, JSS	Success
975	Submarine, LPD, LCF, M-Frigate	Success
980	Submarine, M-Frigate	Success
992	Submarine, LCF, LCF, LCF, M-Frigate, M-Frigate	Success
994	LPD, M-Frigate, JSS	Success
1003	Submarine, LCF, LCF, LCF	Success

Table B.3: Mission results summary. Test case 1, war scenario. Composition: [7, 7, 6, 8, 8, 8, 7] part 3

Mission day	Selected vessels	Mission result
1012	Submarine, M-Frigate	Failed: Battle undecided.
1023	LPD, M-Frigate, JSS, JSS, JSS	Success
1028	Submarine, LCF, M-Frigate, M-Frigate	Success
1040	LPD, LCF, CSS, CSS	Success
1041	Submarine, Submarine, Submarine, M-Frigate, Patrol, Patrol, CSS	Success
1054	LPD, M-Frigate	Success
1057	Submarine, LPD, LPD, LPD, LPD, M-Frigate	Success
1058	Submarine, JSS, JSS, JSS	Success
1075	LPD, LCF	Failed: Battle undecided.
1076	Submarine, M-Frigate	Failed: Battle undecided.
1077	LCF, M-Frigate, CSS, CSS, CSS, CSS, CSS, CSS	Success
1078	-	Failed: Can not meet mission requirements
1091	Submarine, Submarine, Submarine, M-Frigate, Patrol, Patrol	Success
1122	Submarine, LPD, LCF, M-Frigate, M-Frigate	Success
1132	LCF, M-Frigate	Success
1139	Submarine, M-Frigate, M-Frigate, JSS	Success
1158	M-Frigate, M-Frigate, JSS	Success
1160	Submarine, LPD, LPD, LCF, LCF, LCF, M-Frigate	Success
1166	LPD, LPD, M-Frigate, CSS, CSS, CSS	Success
1168	LCF, M-Frigate	Success
1174	Patrol, Patrol, JSS	Success
1180	Submarine, Submarine, M-Frigate, Patrol, JSS, JSS, JSS	Success
1184	LPD, CSS, CSS, CSS	Success
1185	JSS	Success
1187	M-Frigate, Patrol, Patrol	Success
1188	LPD, M-Frigate	Success
1205	M-Frigate, CSS, CSS, CSS	Success
1209	LPD, LPD, M-Frigate	Success
1211	Submarine, LCF, JSS	Success
1222	Submarine, LPD, LPD, LCF	Success
1237	LPD, M-Frigate	Success
1240	Submarine, LCF, JSS	Success
1241	Submarine, Submarine, Submarine, LPD, M-Frigate, Patrol, CSS, CSS, CSS	Success
1245	LPD, LPD, LCF, M-Frigate	Success
1249	M-Frigate, JSS, JSS	Success
1252	-	Failed: Can not meet mission requirements
1256	LPD, LPD, M-Frigate, CSS	Success
1260	Submarine, Submarine, Submarine, Patrol	Success
1276	LPD, M-Frigate, CSS, CSS	Success
1312	Submarine, LPD, LPD, LPD, M-Frigate	Success
1318	LCF, M-Frigate	Failed: Battle undecided.
1319	LPD, LPD, M-Frigate, JSS, JSS	Success
1327	Submarine, M-Frigate, Patrol	Success
1334	Submarine, M-Frigate	Success
1349	LPD, JSS	Success
1351	LPD, LPD, M-Frigate	Success
1368	LCF, LCF, LCF	Failed: Battle undecided.
1373	Submarine, M-Frigate, CSS	Success
1384	Submarine, M-Frigate, Patrol	Success
1392	Submarine, LPD, M-Frigate, CSS	Failed: Battle undecided.
1398	LCF, LCF, LCF, LCF	Success
1402	Submarine, LPD, M-Frigate	Failed: Battle lost.
1409	Submarine, LPD, LPD, LPD, M-Frigate, Patrol, Patrol, Patrol	Success

Table B.4: Mission results summary. Test case 1, war scenario. Composition: [7, 7, 6, 8, 8, 8, 7] part 4

Mission day	Selected vessels	Mission result
1412	LPD, M-Frigate, M-Frigate, CSS, CSS	Success
1413	Submarine, M-Frigate	Success
1422	LPD, LCF, CSS	Success
1429	Submarine, Submarine, M-Frigate, CSS	Failed: Battle undecided.
1434	M-Frigate, M-Frigate, CSS	Success
1440	Submarine, LPD, LPD, Patrol, Patrol, Patrol	Success
1450	LCF, M-Frigate, CSS	Success

Table B.5: Mission results summary. Test case 1, war scenario. Composition: [6, 5, 1, 5, 6, 7, 9] part 1

Mission day	Selected vessels	Mission result
1	LPD, LPD, Patrol, CSS	Success
3	Submarine, M-Frigate	Success
12	Submarine, LPD, LCF, Patrol, Patrol	Success
23	Submarine, Submarine, JSS, JSS	Success
30	Submarine, LPD, CSS	Success
42	Submarine, LPD, LCF, Patrol, Patrol	Success
46	M-Frigate, JSS, JSS, CSS, CSS	Success
49	Submarine, LPD, CSS, CSS, CSS, CSS	Success
65	Submarine, M-Frigate	Success
83	Submarine, CSS	Success
85	LPD, M-Frigate, CSS	Success
86	LPD, M-Frigate, Patrol, Patrol, Patrol	Success
97	LPD, LCF, M-Frigate	Success
103	Submarine, Submarine, M-Frigate	Failed: Battle undecided.
112	Submarine, CSS, CSS	Success
113	Submarine, LPD, M-Frigate, CSS	Failed: Battle undecided.
122	-	Failed: Can not meet mission requirements
132	Submarine, LPD, LPD, CSS	Success
133	Submarine, Submarine, LPD, Patrol, CSS	Success
136	M-Frigate, M-Frigate, JSS	Success
157	Submarine, M-Frigate, CSS	Failed: Battle lost.
161	LPD, LPD, M-Frigate, JSS	Success
178	Submarine, Submarine, LPD, M-Frigate, Patrol, Patrol	Success
188	Submarine, M-Frigate	Success
190	LPD, LPD, LPD, M-Frigate, CSS, CSS, CSS, CSS	Success
191	-	Failed: Can not meet mission requirements
224	Submarine, Submarine, Submarine, M-Frigate, Patrol, Patrol, JSS	Success
238	M-Frigate	Failed: Battle lost.
258	LPD, LPD, LPD, LCF	Failed: Battle undecided.
261	Submarine, CSS, CSS, CSS, CSS	Success
262	LPD, Patrol, Patrol, CSS	Failed: Battle undecided.
270	Submarine, Submarine, M-Frigate, Patrol, Patrol, JSS	Success
274	LCF, M-Frigate, Patrol	Success
282	Submarine, Submarine, M-Frigate, JSS	Success
290	M-Frigate, JSS	Failed: Battle undecided.
306	LPD, LPD, LPD, CSS	Failed: Battle undecided.
313	Submarine, Submarine, Submarine, Submarine, Submarine, LCF, M-Frigate, Patrol, Patrol, Patrol	Success
316	-	Failed: Can not meet mission requirements
324	-	Failed: Can not meet mission requirements
330	Patrol, JSS	Failed: Battle undecided.
354	Submarine, CSS	Success
360	Submarine, Submarine, M-Frigate, Patrol	Success
363	M-Frigate, CSS	Success
378	Submarine, Submarine, LCF, CSS	Success
382	Submarine, M-Frigate	Success
391	LPD, M-Frigate, Patrol	Failed: Battle undecided.
393	-	Failed: Can not meet mission requirements
412	LCF, M-Frigate, CSS	Success
420	LPD, M-Frigate	Success
450	Submarine, LPD, M-Frigate, CSS	Failed: Battle undecided.
460	Submarine, Submarine, LCF, Patrol, Patrol, Patrol, JSS	Success
464	LPD, LPD, LPD, M-Frigate	Success
471	-	Failed: Can not meet mission requirements
486	Submarine, LCF, CSS	Failed: Battle undecided.
506	Submarine, Patrol, Patrol	Success

Table B.6: Mission results summary. Test case 1, war scenario. Composition: [6, 5, 1, 5, 6, 7, 9] part 2

Mission day	Selected vessels	Mission result
521	Submarine, LPD	Success
572	Submarine, M-Frigate, CSS	Failed: Battle undecided.
573	-	Failed: Can not meet mission requirements
575	-	Failed: Can not meet mission requirements
594	-	Failed: Can not meet mission requirements
596	Submarine, Submarine, Submarine, Patrol, Patrol, Patrol, Patrol, JSS	Success
632	Submarine, LCF, M-Frigate, JSS	Failed: Battle undecided.
636	LPD, LPD, M-Frigate	Success
638	-	Failed: Can not meet mission requirements
644	-	Failed: Can not meet mission requirements
651	Submarine, CSS	Success
673	M-Frigate, CSS	Success
674	Submarine, LPD, JSS, JSS	Success
675	Submarine, LCF, M-Frigate	Success
683	LCF, M-Frigate	Success
691	LPD, LPD, M-Frigate, CSS	Success
694	Submarine, Patrol	Failed: Battle undecided.
695	-	Failed: Can not meet mission requirements
697	LPD, CSS	Failed: Battle undecided.
710	Submarine, Submarine, Submarine, LPD, LCF, Patrol	Success
718	Submarine, JSS	Success
721	M-Frigate, CSS	Success
728	LPD, M-Frigate	Success
746	LCF, M-Frigate	Success
758	Submarine, LPD, M-Frigate	Success
773	LPD, Patrol	Success
774	Submarine, Submarine, LCF, Patrol, JSS	Success
787	LPD, JSS	Success
791	M-Frigate, JSS	Success
794	Submarine, LPD, M-Frigate, Patrol	Failed: Battle undecided.
796	M-Frigate, JSS	Success
797	-	Failed: Can not meet mission requirements
801	LCF, Patrol, Patrol, CSS	Failed: Battle undecided.
821	Submarine, M-Frigate, Patrol	Success
834	Submarine, LPD, LPD, LCF, CSS	Success
851	M-Frigate, Patrol, JSS	Success
855	LPD, M-Frigate, M-Frigate, JSS	Success
859	Submarine, CSS	Success
861	LPD, LPD, Patrol	Success
875	LCF, JSS	Success
883	Submarine, Patrol, CSS	Success
885	LPD, LPD, M-Frigate	Success
889	Submarine, CSS	Failed: Battle undecided.
901	-	Failed: Can not meet mission requirements
917	M-Frigate, JSS, CSS	Failed: Battle undecided.
929	Submarine, LPD, Patrol, JSS	Failed: Battle undecided.
931	M-Frigate, Patrol, CSS	Success
932	-	Failed: Can not meet mission requirements
949	-	Failed: Can not meet mission requirements
952	-	Failed: Can not meet mission requirements
953	-	Failed: Can not meet mission requirements
955	Submarine, Submarine, LPD, Patrol, Patrol	Success
975	LPD, M-Frigate, Patrol, CSS	Failed: Battle undecided.
980	Submarine, M-Frigate	Success
992	M-Frigate, JSS	Success
994	-	Failed: Can not meet mission requirements

Table B.7: Mission results summary. Test case 1, war scenario. Composition: [6, 5, 1, 5, 6, 7, 9] part 3

Mission day	Selected vessels	Mission result
1003	M-Frigate, JSS, CSS	Failed: Battle lost.
1012	Submarine, M-Frigate	Success
1023	Submarine, Submarine, Submarine, LPD, LPD, Patrol, Patrol, Patrol, JSS	Success
1028	LPD, M-Frigate, Patrol	Success
1040	LPD, LPD, M-Frigate, CSS, CSS	Success
1041	-	Failed: Can not meet mission requirements
1054	Submarine, Submarine, Submarine, Submarine, M-Frigate, Patrol, Patrol	Success
1057	Submarine, LPD, LPD, LPD, M-Frigate, Patrol	Success
1058	JSS, JSS, JSS	Success
1075	LCF, JSS, JSS, JSS	Success
1076	-	Failed: Can not meet mission requirements
1077	-	Failed: Can not meet mission requirements
1078	-	Failed: Can not meet mission requirements
1091	M-Frigate	Success
1122	Submarine, Submarine, LPD, M-Frigate	Success
1132	LCF, Patrol	Success
1139	-	Failed: Can not meet mission requirements
1158	M-Frigate, CSS, CSS	Failed: Battle undecided.
1160	-	Failed: Can not meet mission requirements
1166	LPD, LCF, JSS, JSS, JSS	Success
1168	-	Failed: Can not meet mission requirements
1174	LPD, LPD, Patrol, Patrol, JSS	Success
1180	-	Failed: Can not meet mission requirements
1184	LPD, JSS	Failed: Battle undecided.
1185	LPD, LPD, JSS	Success
1187	Submarine, Submarine, LCF, Patrol, Patrol	Success
1188	-	Failed: Can not meet mission requirements
1205	-	Failed: Can not meet mission requirements
1209	LPD, Patrol, Patrol	Success
1211	Submarine, Patrol, JSS	Success
1222	Submarine, Submarine, LPD, LPD, Patrol, Patrol	Success
1237	Submarine, M-Frigate	Success
1240	LPD, LCF, M-Frigate	Failed: Battle undecided.
1241	-	Failed: Can not meet mission requirements
1245	Patrol, JSS, JSS, CSS	Success
1249	-	Failed: Can not meet mission requirements
1252	-	Failed: Can not meet mission requirements
1256	-	Failed: Can not meet mission requirements
1260	Submarine, LPD	Failed: Battle undecided.
1276	Submarine, Submarine, LPD, LPD, LPD, M-Frigate	Success
1312	-	Failed: Can not meet mission requirements
1318	M-Frigate, Patrol	Success
1319	Submarine, Submarine, LPD, LPD, LPD, LPD	Success
1327	-	Failed: Can not meet mission requirements
1334	-	Failed: Can not meet mission requirements
1349	Patrol, JSS	Success
1351	-	Failed: Can not meet mission requirements
1368	LCF, Patrol, JSS	Success
1373	Submarine, Submarine, Submarine, M-Frigate, Patrol, Patrol, Patrol, JSS, JSS, JSS	Success
1384	-	Failed: Can not meet mission requirements
1392	Submarine, M-Frigate, JSS, JSS	Success
1398	LCF, Patrol	Success
1402	-	Failed: Can not meet mission requirements

Table B.8: Mission results summary. Test case 1, war scenario. Composition: [6, 5, 1, 5, 6, 7, 9] part 4

Mission day	Selected vessels	Mission result
1409	-	Failed: Can not meet mission requirements
1412	LPD, M-Frigate, Patrol, CSS	Success
1413	-	Failed: Can not meet mission requirements
1422	LPD, LPD, LPD, LPD, LCF, JSS, JSS, JSS	Success
1429	-	Failed: Can not meet mission requirements
1434	-	Failed: Can not meet mission requirements
1440	Submarine, Submarine, Submarine, Patrol, Patrol	Success
1450	LCF, Patrol, JSS, JSS, JSS	Success

Table B.9: Mission results summary. Test case 1, peace scenario. Composition: [2, 2, 1, 4, 0, 1, 2]

Mission day	Selected vessels	Mission result
5	Submarine, Submarine, M-Frigate	Success
15	LPD, M-Frigate, JSS, CSS	Success
43	Submarine, LPD, M-Frigate, JSS, CSS	Success
55	M-Frigate	Failed: Battle lost.
77	-	Failed: Can not meet mission requirements
99	Submarine, LPD	Success
113	Submarine, LCF, CSS	Success
132	Submarine, M-Frigate	Failed: Battle undecided.
231	Submarine, LPD, M-Frigate	Success
259	M-Frigate	Failed: Battle lost.
279	Submarine, LPD	Success
281	Submarine, LPD, CSS	Success
302	LPD, CSS	Success
339	LPD, LCF, CSS	Failed: Battle undecided.
347	Submarine, Submarine, JSS	Success
376	LPD, M-Frigate, CSS	Success
389	M-Frigate	Success
392	-	Failed: Can not meet mission requirements
466	LPD, LCF, CSS	Success
467	Submarine, M-Frigate, CSS	Success
484	Submarine, LPD, M-Frigate	Failed: Battle undecided.
494	-	Failed: Can not meet mission requirements
535	LPD, LCF, CSS	Success
542	LPD, M-Frigate	Success
593	Submarine, LPD, CSS	Failed: Battle undecided.
617	Submarine, LPD, LPD, M-Frigate, CSS	Success
658	Submarine, CSS	Failed: Battle undecided.
666	Submarine, LPD, M-Frigate, CSS	Failed: Battle undecided.
673	-	Failed: Can not meet mission requirements
682	Submarine, LCF, CSS	Success
703	-	Failed: Expected loss.
761	LPD, LCF, CSS	Success
818	Submarine, LPD, M-Frigate, M-Frigate, JSS	Success
835	LPD, CSS	Success
908	Submarine, CSS	Success
942	Submarine, LPD, M-Frigate, CSS	Success
962	Submarine, LPD, M-Frigate	Success
1028	Submarine, LCF, JSS	Success
1038	Submarine, LPD, M-Frigate	Success
1045	Submarine, M-Frigate, CSS	Success
1076	Submarine, LPD, M-Frigate	Success
1095	M-Frigate, JSS	Success
1162	LPD, M-Frigate	Success
1175	Submarine, M-Frigate, JSS	Success
1177	LPD, LCF, M-Frigate	Failed: Battle undecided.
1192	-	Failed: Can not meet mission requirements
1213	Submarine, LPD, CSS, CSS	Success
1284	LCF, M-Frigate	Success
1321	M-Frigate	Success
1343	Submarine, M-Frigate, CSS	Success
1358	Submarine, M-Frigate, M-Frigate, CSS	Failed: Battle undecided.

Table B.10: Mission results summary. Test case 1, peace scenario. Composition: [5, 1, 6, 8, 2, 2, 1]

Mission day	Selected vessels	Mission result
5	Submarine, Submarine, M-Frigate, M-Frigate	Success
15	Submarine, LPD, LCF, LCF	Failed: Battle undecided.
43	LCF, M-Frigate, M-Frigate, Patrol, Patrol	Success
55	Submarine, LCF, LCF, M-Frigate	Success
77	LPD, M-Frigate, M-Frigate, JSS	Success
99	Submarine, JSS	Success
113	Submarine, Submarine, M-Frigate, JSS	Success
132	Submarine, M-Frigate	Success
231	LCF, Patrol, JSS	Failed: Battle undecided.
259	M-Frigate	Failed: Battle lost.
279	Patrol, JSS	Success
281	Submarine, JSS	Success
302	JSS	Failed: Battle undecided.
339	Submarine, LCF, JSS	Success
347	Submarine, Submarine, LPD, Patrol	Success
376	Submarine, JSS	Failed: Battle lost.
389	M-Frigate	Failed: Battle undecided.
392	LCF, M-Frigate	Success
466	LCF, LCF, M-Frigate	Success
467	Submarine, Submarine, CSS	Failed: Battle undecided.
484	LCF, M-Frigate	Success
494	Submarine, Submarine, LCF, LCF, LCF, LCF, Patrol, JSS	Success
535	LPD, LCF, CSS	Success
542	LCF, LCF, M-Frigate, JSS	Success
593	Submarine, Submarine, Patrol, CSS	Success
617	Submarine, LCF, JSS	Failed: Battle lost.
658	Submarine, Submarine, Patrol, CSS	Success
666	-	Failed: Can not meet mission requirements
673	-	Failed: Can not meet mission requirements
682	-	Failed: Can not meet mission requirements
703	Submarine, LPD, LCF, LCF, Patrol	Success
761	Submarine, LPD, LCF	Success
818	Submarine, LPD, LCF, LCF, LCF, LCF, CSS	Success
835	-	Failed: Can not meet mission requirements
908	Submarine, Submarine, Patrol, CSS	Success
942	Submarine, LPD, LCF, M-Frigate	Failed: Battle undecided.
962	LCF, M-Frigate, M-Frigate	Failed: Battle undecided.
1028	Submarine, LCF, Patrol, Patrol, CSS	Success
1038	Submarine, LCF, M-Frigate, M-Frigate, M-Frigate	Success
1045	Submarine, Submarine, M-Frigate, Patrol, Patrol, CSS	Success
1076	Submarine, LPD, M-Frigate, M-Frigate	Success
1095	-	Failed: Can not meet mission requirements
1162	LPD, M-Frigate	Success
1175	-	Failed: Can not meet mission requirements
1177	LCF, M-Frigate, Patrol	Success
1192	Submarine, LCF, LCF, LCF	Success
1213	-	Failed: Can not meet mission requirements
1284	LCF, M-Frigate	Success
1321	M-Frigate	Success
1343	M-Frigate, M-Frigate, Patrol, Patrol, CSS	Success
1358	M-Frigate, M-Frigate, M-Frigate, Patrol, Patrol, CSS	Success

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