Towards unmanned cargo ships

A task based design process to identify economically viable low and unmanned ship concepts

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Unmanned and low-manned transport has increasingly been studied this past decade. While there have been successful trials for autonomous navigation, unmanned cargo ships are not commercially available yet. First, this dissertation investigates how changes to a ship's systems and organizational structure can affect the crew's size and composition. Then, a cost benefit analysis determines the economic viability of these concepts. This research concludes with feasible intermediate steps between a conventional ship and a fully unmanned ship.

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Carmen Kooij

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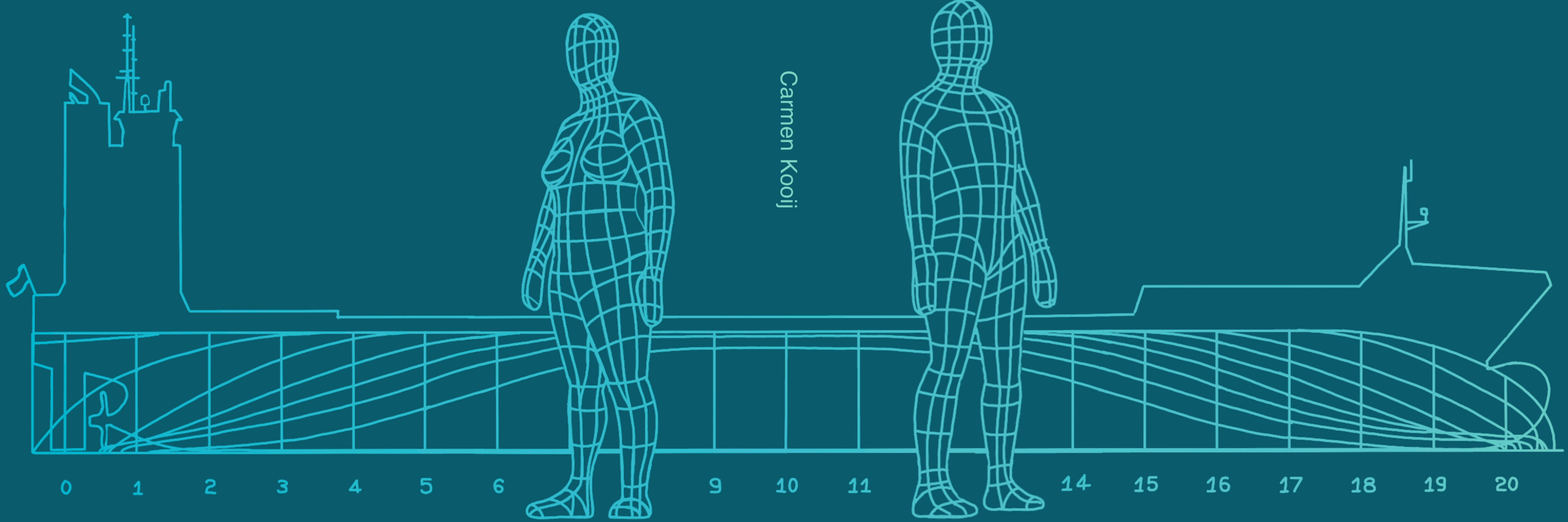

TOWARDS UNMANNED CARGO SHIPS

A TASK BASED DESIGN PROCESS TO IDENTIFY ECONOMICALLY VIABLE LOW AND UNMANNED SHIP CONCEPTS

Towards unmanned cargo ships

A task based design process to identify economically viable low and unmanned ship concepts

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. dr. ir. T.H.J.J. van der Hagen,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op dinsdag 16 december 2021 om 10:00 uur

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JOINT INDUSTRY PROJECT AUTONOMOUS SHIPPING

NOVIMAR VESSELTRAIN

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Voor papa,
die dacht dat promoveren wel iets voor mij zou zijn.
Voor mama,
die mij geleerd heeft dat je alles kan, als je er maar bij kunt zingen

Contents

SUMMARY

OVER the last years, a lot of research has been performed into the technical, economical and societal feasibility of unmanned ships. This research has mainly focussed on individual technical aspects, or combining several technical aspects into a full design of a ship. However, it has not explicitly been ensured that the changes made to the ship are enough to replace all the tasks that the crew currently performs. Additionally, there is very little research on the development path towards unmanned ships.

To ensure that all the crew's tasks are properly addressed in low-manned ship concepts, this study analyses them in detail. Additionally, systematically investigating what is required to replace certain (groups of) tasks allows for identification of economically viable low manned ship and manning concepts. The research is performed using a short sea container vessel as a case study.

The goal of this study is: *To identify technically feasible and economically viable ship and manning concepts that are on the likely development path towards unmanned ships.*

To reach this goal, the following questions must be answered:

1. What is the role of the crew in the fulfilment of the functions of the ship?
2. How can the effect of replacing crew tasks on the composition of the crew be determined?
3. What technically feasible options are available to replace crew tasks on board?
4. What are the costs associated with these technically feasible options?
5. What ship and manning concepts are likely candidates for the development path towards unmanned ships?

The steps that are taken to answer the questions are presented in Figure 1. The first questions is answered by setting up a functional breakdown of the key functions of a ship. This functional breakdown is used as a guide to find the crew tasks. The identification of the crew tasks is done through a field study on board and expert interviews. The task analysis resulted in a list of 41 tasks that are performed by the crew. However, not all tasks need to be replaced individually. For example, the mooring process consists of multiple different tasks, but replacing only a few of those is not logical. Therefore the tasks are clustered together in such a way that they can be replaced with one solution. This results in 11 clusters of tasks;

- Open water navigation
- Near shore navigation
- Mooring
- Maintenance on deck

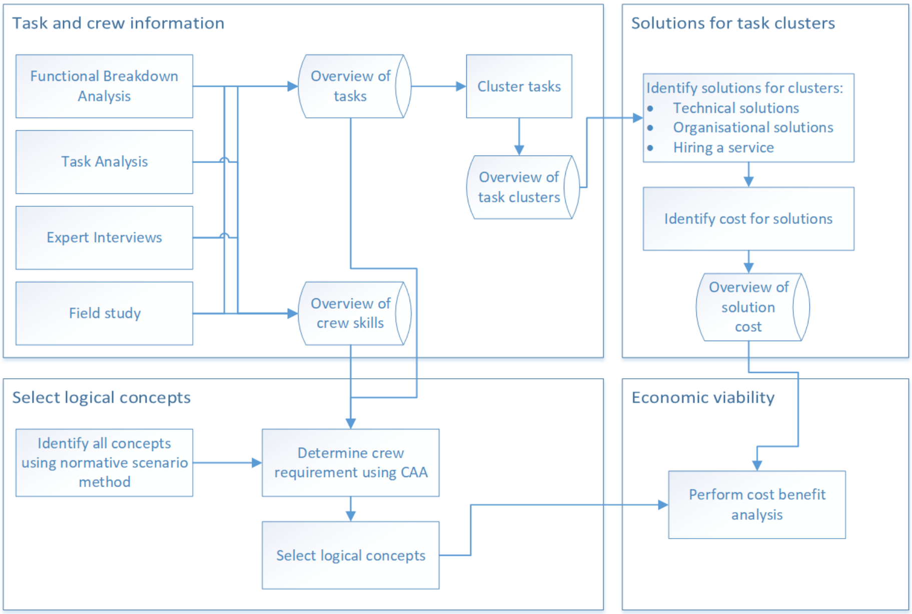


Figure 1: Overview of the steps taken in this dissertation

- Maintenance in the engine room
- Bunkering
- Administration
- Cargo conditioning
- Port supervision
- Crew support
- Responsibility

The second question addresses the method by which the required crew composition can be determined in a situation where tasks have been replaced. The mathematical term for a problem in which tasks are assigned over crew members is an assignment problem. There are multiple methods to solve this type of problem, depending on several factors. In this study, a greedy algorithm is used. This algorithm assigns the tasks to crew members to determine the cheapest crew that can perform the provided workload.

The third and fourth research questions are answered together. For each of the clusters identified in Chapter 2, the possible solutions are identified. There are three types of solutions; technical solutions, solutions that use a shore crew, and solutions where a service is used. After that, cost estimations of the solutions are made based on available literature. The costs are categorized as additional investment cost, shore crew cost, and usage cost. Together these costs make up the total cost of the solution.

In the fifth chapter, economically viable ship and manning concepts are identified. The different concepts are generated by systematically replacing, or not replacing, each of the clusters identified in Chapter 1. This results is2^{11} = 2048 different concepts. By using the algorithm that is explained in Chapter 3 the required crew for each concept can be determined. However, not all of these concepts are practical or economically viable. For example, there are multiple concepts which involve the replacement of clusters without influencing the size of the crew. This is due to the fact that the journey of a ship can be split into three phases, and not every cluster affects the crew in all travel phases. To select the most promising concepts, a selection method is applied with the following selection criteria:

1. The clusters that are removed all take place in the normative phase of the voyage (i.e., the phase that requires the most crew members). Removing crew members from another phase will not lead to a reduction of the required crew.
2. The economic impact of the clusters is investigated. Scenarios will only be considered if it is likely that there is potential for an economic benefit for the ship owner. This is not a full economic analysis but based on the estimated implementation cost of the clusters as determined in Chapter 4.
3. Of the remaining clusters, the replacement options with the highest TRL or the shortest time to maturity time are selected.
4. The cluster with the highest impact on the size of the crew is selected.

This selection process results in 6 concepts. The concepts, along with the required crew calculated by the algorithm and the total reduction in crew cost, are presented in Table 1.

To determine if the selected concepts are economically viable, a cost-benefit analysis is performed. The basis of the cost-benefit analysis is that the cost of the replacement solutions should be lower than the savings of the crew cost and the crew-related cost. The results of the cost-benefit analysis are shown in Table 2. The analysis is performed with a best case scenario and a worst case scenario, which are represented by the two costs in the table. The table shows that out of the six concepts, four are economically favourable compared to the fully manned base case. The final unmanned concept consists of two variants, one with multiple diesel generators and diesel electric propulsion, and a second with a Proton Exchange Membrane Fuel Cell (PEMFC). The fuel cell is added to the comparison because the feasibility of a diesel engine as propulsion for an unmanned ship is disputed.

The final step is to perform a generalisation of the results to see how the results can be applied to the world fleet. To that end, the effects of the number of port calls, the installed power the size of the crew, and the crew wages are investigated. These generalisations lead to the following conclusions:

- Ships with fewer port calls have a larger potential benefit than ships with more port calls. A lower number of port calls lowers the cost of the onshore personnel required, which is a significant cost factor.
- Ships with a lower installed power have higher potential percentagewise savings and ships with a higher installed power have lower potential percentagewise sav-

Table 1: Summary of the selected logical concepts, applicable for the selected reference ship

	Required crew during Loading and unloading	Required crew during Arrival and departure	Required crew during Normal sailing	Crew cost reduction per month [€]
Base case	9	9	11	0
Concept 1: Partial replacement of navigation	9	9	8	5,600
Concept 2: Replacement of mooring and port supervision	6	3	8	16,400
Concept 3: Replacement of maintenance on deck, administration and cargo conditioning	5	4	5	33,400
Concept 4: Redistributing the cooking task	4	4	4	38,800
Concept 5: Replacement of near shore navigation, bunkering and moving responsibility to chief engineer	2	1	2	65,200
Concept 6: Replacing maintenance in engine room, responsibility and crew support	0	0	0	97,800

ings. This is due to the lower investment cost for the propulsion system and the lower associated costs.

- The size of the engine room crew largely determines how many crew members remain on board before the final concept. In the final low manned concept the only crew members on board are the engineering crew.
- Ships with a larger crew have a higher savings potential and thus higher percentagewise savings. By having a larger crew, more crew members can be taken off the ship. The money that is saved by removing the crew members can be put towards replacement solutions for their tasks.
- The economic viability of low manned ship concepts strongly depends on the wages of the crew. These wages vary strongly, depending on the flag under which the ship is registered and the nationality of the crew members. For operators that use low wage crews and operate in areas where shore-based activities are expensive, it will be hard or impossible to achieve economic benefit from low manned ship concepts.

To summarise, this dissertation presents a method to identify and select logical low manned concepts. A cost-benefit analysis is performed that shows that several of the selected concepts are economically viable, when compared to the fully manned conven-

Table 2: Net benefit for the best and worst case scenarios

Concept	Size of the crew	Cost change [%]
Base case	11	
Concept 1	9	-1.1%
Concept 2	8	1.7% to 3.9%
Concept 3	5	-1.6% to 1.0%
Concept 4	4	-2.8% to -0.2%
Concept 5	2	-5.4% to -1.6%
Concept 6 Diesel generator	0	-11.4% to -6.5%
Concept 6 PEMFC	0	20.9% to 93.3%

tional ship. This, combined with the results presented above show that the goal of this research has been reached.

SAMENVATTING

De laatste jaren is er veel onderzoek verricht naar de technische, economische en maatschappelijke haalbaarheid van onbemande schepen. Deze onderzoeken richten zich vooral op individuele technische aspecten, of het combineren van een aantal van deze oplossingen tot het ontwerp van een onbemand schip. Het is echter niet expliciet gecontroleerd of deze aanpassingen leiden tot een volledige vervanging van de taken die de bemanning van het schip tijdens de reis uitvoert. Daarnaast is er weinig onderzoek gedaan naar het ontwikkelingspad richting onbemande schepen.

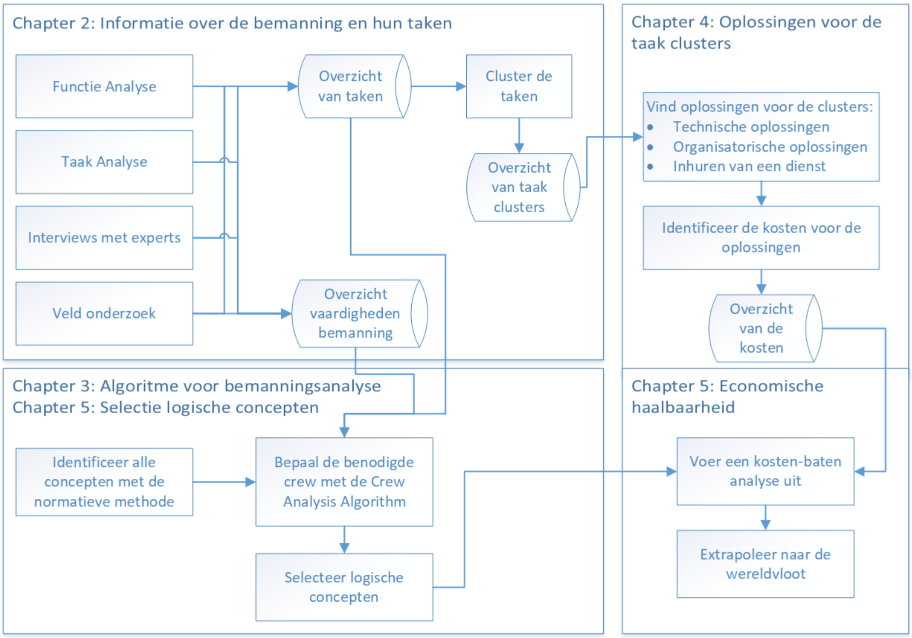
In dit onderzoek worden de taken van de bemanning in detail geanalyseerd om ervoor te zorgen dat alle taken aan bod komen in laag bemande scheepsconcepten. Daarnaast worden economisch haalbare laag bemande scheeps- en bemanningsconcepten geïdentificeerd door systematisch te onderzoeken wat er nodig is om bepaalde (groepen van) raken te vervangen. In dit onderzoek wordt een short sea container ship gebruikt als case study.

Het doel van dit onderzoek is: *Het identificeren van technische en economisch haalbare scheeps- en bemanningsconcepten die op het ontwikkelingspad van onbemande schepen liggen.*

Om dit doel te behalen moeten de volgende vragen beantwoord worden:

- Wat is de rol van de bemanning in het volbrengen van de functies van het schip?
- Hoe kan het effect van het vervangen van taken van de bemanning op de samenstelling van de bemanning worden bepaald.
- Welke technisch haalbare opties zijn er beschikbaar om de taken van de bemanning te vervangen?
- Wat zijn de kosten van deze technisch haalbare opties?
- Welke scheeps- en bemanningsconcepten zijn goede kandidaten voor het ontwikkelingspad richting onbemande schepen.

De stappen die genomen worden om bovenstaande vragen te beantwoorden worden weergegeven in Figuur 2. De eerste vraag wordt beantwoord door het opzetten van een functie analyse van de belangrijkste functies van het schip. Deze functie analyse dient als leidraad voor het vinden van de taken van de bemanning. Het onderzoeken van de taken van de bemanning is gedaan met behulp van een veld onderzoek aan boord van een schip en interviews met verschillende experts. Deze analyse heeft geleid tot een overzicht van 41 taken die de bemanning uitvoert. Echter hoeven niet alle taken individueel te worden vervangen. Zo bestaat bijvoorbeeld het aanmeer proces uit een aantal verschillende taken, maar het vervangen van slechts een van de taken in dat proces is niet logisch. Om die reden worden de taken zodanig samengevoegd dat de ontstane clusters kunnen worden vervangen met 1 oplossing. Dit resulteert in 11 clusters:



Figuur 2: overzicht van de stappen die genomen zijn in dit onderzoek

- Aanleggen
- Navigatie in open water
- Navigatie dicht bij de kant
- Onderhoud op het dek
- Onderhoud in de machinekamer
- Ondersteuning van de bemanning
- Zorg voor de lading
- Haventoezicht
- Vernatwoordelijkheid
- Bunkeren
- Administratie

De tweede vraag richt zich op de methode waarmee de benodigde bemanningssamenstelling kan worden bepaald als er taken vervangen zijn. De wiskundige term voor een probleem waarbij taken over bemanningsleden worden verdeeld is een *assignment* problem. Er zijn verschillende manieren om een dergelijk probleem op te lossen, afhankelijk van een aantal factoren. In dit onderzoek wordt gebruik gemaakt van een *greedy algorithm*. Dit algoritme wijst taken toe aan bemanningsleden om zo de goedkoopste bemanning te bepalen die de gegeven taken kan uitvoeren.

De derde en vierde onderzoeksvragen worden samen beantwoord. For elk van de clusters die in Hoofdstuk 2 bepaald zijn worden mogelijke oplossingen onderzocht. Er zijn 3 soorten oplossingen; technische oplossingen, oplossingen waarbij een bemanning op de kant gebruikt wordt en oplossingen waarbij een service ingehuurd wordt. Vervolgens wordt er een kostenschatting gemaakt op basis van bestaande literatuur. Deze kosten worden verdeeld in extra investeringskosten, kosten voor personeel op de kant en gebruikskosten. Bij elkaar opgeteld leidt dit tot de totale kosten van een oplossing.

In Hoofdstuk 5 worden economisch haalbare scheeps- en bemanningsconcepten geïdentificeerd. De verschillende concepten worden gegenereerd door elk cluster, zoals bepaald in hoofdstuk 1, systematisch wel of niet te vervangen. Dit leidt tot $2^{11} = 2048$ verschillende concepten. Door gebruik te maken van het algoritme uit hoofdstuk 3 kan de benodigde bemanning voor elk van de concepten worden bepaald. Niet elk van deze concepten zijn praktisch of economisch haalbaar. Zo zijn er bijvoorbeeld verschillende concepten waarbij een of meerdere clusters worden vervangen zonder dat dit invloed heeft op de grootte van de bemanning. Dit is omdat de reis van het schip opgedeeld is in 3 verschillende reisfases en niet elk cluster betrekking heeft op elk van de reisfases. Om uit de vele mogelijke concepten de meest veelbelovende te kiezen worden de volgende methode toegepast:

1. De clusters die vervangen worden vinden plaats in de maatgevende reisfase (dat wil zeggen de reisfase waar de meeste bemanningsleden nodig zijn). Het vervangen van bemanningsleden in andere reisfasen heeft geen effect op de grootte van de bemanning.
2. De economische impact van het vervangen van de taken wordt onderzocht. Concepten worden alleen meegenomen in de overweging als er een economisch voordeel te verwachten is. Dit is geen volwaardige economische analyse, maar is gebaseerd op de kostenschatting die gedaan is in Hoofdstuk 4.
3. Uit de resterende clusters worden de opties met de hoogste TRL (Technology Readiness Level) of de kortste implementatietijd geselecteerd.
4. Het cluster met de grootste impact op de grootte van de bemanning wordt geselecteerd.

Dit selectie proces resulteert in 6 concepten. De concepten zijn, samen met de benodigde bemanning en de totale besparing op bemanningskosten te vinden in Tabel 3.

Om te bepalen of de geselecteerde concepten economisch haalbaar zijn is er een kosten-baten analyse uitgevoerd. De basis van deze kosten-baten analyse is dat de kosten van de vervangingsoplossingen lager moeten zijn dan de besparingen op de bemanning en bemanning gerelateerde kosten. De resultaten van de kosten-baten analyse is te vinden in Tabel 4. De analyse is uitgevoerd met een beste en een slechtste geval, die worden weergegeven door de twee verschillende waardes in de tabel. De tabel laat zien dan van de zes concepten er 4 economisch voordelig zijn ten opzichte van de volledige bemande basis situatie. Het onbemande concept (concept 6) bestaat uit twee varianten, één waarbij gebruik wordt gemaakt van meerdere diesel generatoren en dieselelektrische voortstuwing, en een tweede waarbij het schip is uitgerust met een Proton Exchange Membrane brandstof cel (PEMFC). De brandstofcel is toegevoegd aan de vergelijking omdat de haalbaarheid van diesel voorstuwing in de literatuur in twijfel wordt getrokken.

Tabel 3: Samenvatting van de geselecteerde concepten voor het referentieschip

	Laden en lossen	Aankomst en vertrek	Varen in open water	Kostenvermindering bemanning per maand [€]
Basis situatie	9	9	11	0
Concept 1: Vervangen van open water navigatie	9	9	8	5,600
Concept 2: Vervangen van aanleggen en haven toezicht	6	3	8	16,400
Concept 3: Vervangen van onderhoud op het dek, administratie en zorg voor de lading	5	4	5	33,400
Concept 4: Verplaatsen van de kook taak	4	4	4	38,800
Concept 5: Vervangen van navigatie dicht bij de kant, bunkeren en verantwoordelijkheid naar de hoofdwerktuigkundige	2	1	2	65,200
Concept 6: Vervangen van onderhoud in de machinekamer, verantwoordelijkheid en ondersteuning van de bemanning	0	0	0	97,800

De laatste stap is om de resultaten uit de case study te generaliseren om te kijken hoe de resultaten van toepassing op de wereldvloot. Om dat te doen, is er onderzoek gedaan naar de invloed van het aantal havenaankomsten, het geïnstalleerd vermogen, de grootte van de bemanning en de hoogte van de bemanningskosten. Deze generalisatie heeft tot de volgende conclusies geleid:

- Schepen met minder aankomsten in de haven hebben grotere potentiele besparingen dan schepen met meer aankomsten. Hoe minder aankomsten in de haven, hoe lager de kosten zijn voor personeel aan de kant. De kosten voor het personeel aan de kant zijn een significante kostenpost.
- Schepen met een lager geïnstalleerd vermogen hebben hogere potentiele procentuele besparingen dan schepen met een hoger geïnstalleerd vermogen. Dit is door de lagere investeringskosten in de voortstuwing en de lagere daaraan gerelateerde kosten.
- De grootte van de bemanning in de machinekamer bepaald grotendeels hoeveel bemanningsleden er over blijven voor de laatste concepten. In concept 5 is er alleen nog bemanning in de machinekamer aanwezig.
- Schepen met een grotere bemanning hebben een grotere mogelijke besparing en

Tabel 4: Resultaten van de kosten baten analyse voor het beste en het slechtste geval

Concept	Benodigde bemanning	Verandering in kosten [%]
Basis situatie	11	
Concept 1	9	-1.1%
Concept 2	8	1.7% to 3.9%
Concept 3	5	-1.6% to 1.0%
Concept 4	4	-2.8% to -0.2%
Concept 5	2	-5.4% to -1.6%
Concept 6 Diesel generator	0	-11.4% to -6.5%
Concept 6 PEMFC	0	20.9% to 93.3%

daarmee ook een grotere procentuele besparing. Bij een grotere bemanning kunnen er meer mensen van het schip gehaald worden. Het geld wat bespaard wordt door het verwijderen van de bemanning kan gebruikt worden voor vervangende oplossingen.

- De economische haalbaarheid van laag bemande schepen is grotendeels afhankelijk van de loonskosten van de bemanning. Het salaris van de bemanning varieert significant, afhankelijk van de vlag waaronder het schip geregistreerd is en de nationaliteit van de bemanningsleden. Voor scheepseigenaren die varen met een bemanning die een laag salaris krijgt maar die varen in gebieden waar personeel op de kant relatief duur is, is het lastig om economisch voordeel te halen uit laag bemande schepen.

Samenvattend presenteert deze dissertatie een methode die gebruikt kan worden om logische laag bemande scheeps- en bemanningsconcepten te vinden. Er is een kostenbaten analyse uitgevoerd die aantoont dat verschillende concepten economisch haalbaar zijn in vergelijking met een volledig bemand conventioneel schip. De resultaten hierboven en deze conclusie betekenen samen dat het doel van dit onderzoek bereikt is.

Abbreviations and definitions

Conventional ship	Ship as we now know it, manned and controlled by a crew on board.
Unmanned ship	Ship that has no crew on board while it is sailing, control takes place remotely, either by a human operator or by an autonomous navigation system with human oversight. People can be involved in the operational chain.
Autonomous ship	Ship controlled by an autonomous navigation system, can be either manned or unmanned.

PEMFC	Proton Exchange Membrane Fuel Cell
TRL	Technology Readiness Level
OPEX	Operational Expenditure
Colregs	Collision Regulations
SCC	Shore Control Centre
CAA	Crew Analysis Algorithm
ABS	Able Bodied Seaman
OS	Ordinary Seaman
sfc	Specific Fuel Consumption

1

INTRODUCTION

Hundreds of years ago, early fishermen tied their rudders in a fixed position to free up manpower for fishing. The automatic steering system was introduced on merchant ships in the early 1920s. Before that, the ship was steered by dedicated crew members for whom the steering of the ship was their sole responsibility [9]. Nowadays, an autopilot steers the ship for long periods of time. Crew members only take control of the ship in specific situations.

In the past, crew reductions have mostly taken place under the influence of increasing technical capabilities or the introduction of new technologies. For example, the introduction of the diesel engine meant that the required crew in the engine room could be decreased significantly since it was no longer necessary to manually shovel coal into the engine [8]. The introduction of the radar and other navigational equipment meant that specialised crew for the purpose of location keeping was also no longer required.

The latest increase of technical capabilities is the introduction of autonomy in all transport sectors. Cars can drive themselves, planes can autonomously perform every part of their flight and trains do not always have a driver anymore. Unmanned and autonomous ships have not progressed this far, but in the last decade several projects have looked into many aspects of unmanned and autonomous ships.

However, there is one significant difference between ships and other modes of transport. For cars, trucks, and trains the driver is mainly tasked with navigating or observing a navigation system. The same goes for pilots on board of trains. There is no crew that performs other tasks needed for the operation while a journey is undertaken. For ships this is different. The crew on board of a ship has many more tasks than navigation alone. This thesis investigates the changes to the ship and its organisational structure that are required to develop and operate economically viable low and unmanned ships.

This chapter starts with a discussion of the potential benefits of unmanned and autonomous ships. Next, a literature study is performed that looks into the research that has been performed with regards to low-manned, unmanned and autonomous ships. This literature study leads to a gap analysis and subsequent research questions that will be addressed in this thesis. Finally, the scope of this research is determined.

1.1. THE POTENTIAL BENEFITS OF UNMANNED AND AUTONOMOUS SHIPS

There are several reasons why the industry is interested in unmanned and autonomous systems. On the one hand, there is a push from the industry to lower the required number of crew members due to shortages and increasing wages [11]. On the other hand, the availability of technology and successes in other transport areas have shown what is possible and have started a push in the direction of unmanned and autonomous ships.

It is estimated that in 2025 there will be a shortage of 147,500 officers in the world merchant fleet [11]. This expected shortage could potentially disrupt world trade, which is largely dependent on maritime transport. One of the ideas to combat this shortage is to automate some, or all, tasks on board of ships to create low-manned, or unmanned ships. In addition to solving the crew shortage, unmanned and autonomous ships have other potential benefits. First and foremost, having a smaller crew (or no crew at all) can significantly decrease important aspects of the operational cost. For the largest ocean-going vessels, the crew cost is only a fraction of the operational cost (i.e., typically only a few percent) but for a smaller ships like short sea vessels this number is significantly higher. Figure 1.1 shows the distribution of the operational expenditures (OPEX) for short sea container vessels. Here the crew cost is approximately 22% of the total operational cost. Decreasing the operational cost by such a large number can either increase the profit margin significantly, or it can have a significant impact on the required freight rates, giving the company an competitive edge. However, investing in autonomy is a double edged sword as reducing the size of the crew will bring along additional cost for replacement solutions.

Next, it is believed that having a computerised navigation system will decrease the number of accidents that happen between ships. A significant percentage of accidents, somewhere between 70 and 90%, is attributed to human error [62]. Although this figure does not mention how many accidents are avoided due to the capability of crew members to solve complex and unconventional problems, it does indicate a potential for significant improvement of safety.

These factors mean that there is significant potential benefit to justify future research into unmanned ships. In the next section, a review of the current developments is performed, showing where the focus of the research effort is currently placed.

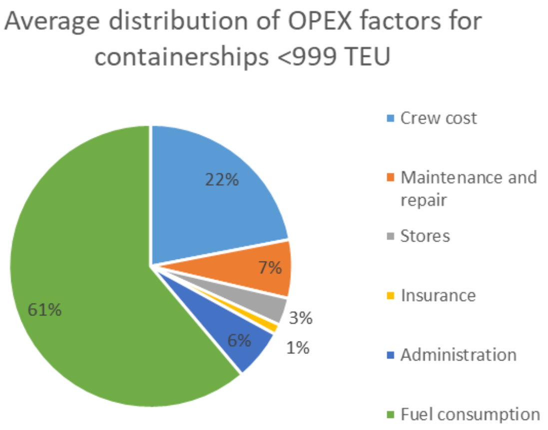


Figure 1.1: Average OPEX distribution for short sea cargo vessels smaller than 999 TEU [crew cost obtained from JR shipping, fuel cost calculated from [15], MGO cost on March 12, 2021 and other percentages taken from [55]]

1.2. REVIEW OF CURRENT DEVELOPMENTS

When investigating the feasibility of new technologies, there are several layers of feasibility that are of interest. The first is technical feasibility which determines if it is even possible to build an unmanned and autonomous ship. The second step is to look at economic feasibility, to determine if it is likely that that shipping companies will invest into these types of ships. Finally there is the societal and political feasibility, which focusses on the opinion of the public and the government [19]. This review of the literature looks into the research that has been performed into each of the different types of feasibility. Figure 1.2 shows the different types of research performed, set against the different types of feasibility.

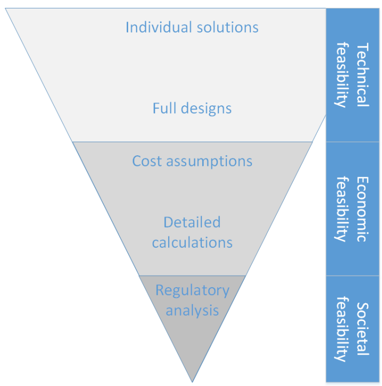


Figure 1.2: Overview of found literature, combined with the different types of feasibility. Source: Author

1

1.2.1. TECHNICAL FEASIBILITY

Technical feasibility focusses on the possibility of building a working unmanned and autonomous ship. This is regardless of the cost to the ship owner. Figure 1.2 shows that the first step of technical feasibility is the investigation of individual solutions for parts of the problem. For unmanned shipping, challenges such as navigation, maintenance of the propulsion system, mooring and communication have been identified. These elements have been investigated individually.

For navigation, the focus lies on sailing without human input, i.e., track keeping, and following the collision regulations (Colregs)[7, 45, 56, 79, 92]. In the last few years, several full scale tests of collision avoidance software have been performed in a controlled environment. In the Netherlands, a consortium of 17 partners collaborated to organise sea trails. During these trails, basic avoidance manoeuvres were performed with some success [33]. In Finland Rolls Royce and Finnferries collaborated to have a car ferry sail autonomously between two places, with several obstacles in between [71]. A good navigation system requires input from its surroundings, and therefore a good method for getting situational awareness (i.e., a sensor suite) is also required [34, 64]. In lot of research into fully autonomous ships, a shore control centre (SCC) is introduced. This SCC monitors several ships and is manned at all times [44].

The communication of data between a SCC and the ships it is monitoring is a critical part of the communication of the unmanned ship [34, 70]. Transferring the data between the ship and shore requires a robust communication system capable of sending and receiving large data files [34]. However, there are more challenges. It is also important for the ship to communicate clearly where it is going to any human nearby without having a human operator on board [63].

Several unmanned mooring systems already exist and are in use [14, 47, 50]. These systems work with either magnets or suction cups, or use small cranes to bring the lines to shore and interface with the existing infrastructure.

Another key aspect of designing and operating an unmanned ship is its propulsion. A conventional ship is generally equipped with a diesel engine. This engine requires a significant amount of maintenance and can only run without an engineer for a short period of time. This means that either the diesel engines need to be improved significantly to be able to run for extended periods of time, for example by increasing the redundancy of the propulsion system [69] or another method of propulsion needs to be found. Both the use of batteries, such as used for the Yara Birkeland and the Revolt [4, 36], and fuel cells [10], have been suggested. These propulsion types have fewer moving parts and therefore possible have less parts that break down due to wear and tear. However, as these methods of propulsion are still new, the knowledge on their failure modes is still relatively limited. This means that anticipating failures becomes very difficult.

The abovementioned research contributes individual parts of the puzzle that is the unmanned and autonomous ship. However, in this research the focus is on one area, without looking the extend of the problem. There are also several large projects that do look into multiple aspects of unmanned and autonomous shipping and therefore combine several of these puzzle pieces. The MUNIN project (www.unmanned-ship.org) , looked into the technical and economic feasibility of an autonomous trans-Atlantic bulk carrier. The AAWA (Advanced Autonomous Waterborne Applications Initiative) project looked into 4 aspects of autonomous sailing; new technologies, legal implications, safety, and market uptake [34]. Another example is the AUTOSHIP project, which looks at short sea and inland shipping and also takes the supply chain into account (www.autoship-project.eu/). The AVATAR project explores the use of zero-emission autonomous ships into cities as an alternative to other modes of transport [5]. Finally a project to note is the Yara Birkeland project, which aimed to have an autonomous, electric ship sailing between two Norwegian ports in 2020. However, setbacks have caused this deadline to be pushed back [36].

The projects mentioned above look into the unmanned ship as a whole. However, while the research mentions that all crew members will be removed from the ship, it is not explicitly ensured that the selected solutions do indeed cover all the tasks that the crew members perform. The key to sailing unmanned is not just automated navigation but also all other tasks that the crew members perform. By not investigating the tasks and functions of the crew, it is uncertain that all their tasks are covered. This is an important knowledge gap to be covered.

1.2.2. ECONOMIC FEASIBILITY

The section above focused on the technical feasibility of unmanned shipping. In addition to technical feasibility, the economic viability is important. Not all research addresses the economics of the proposed solution. However, there are several that give an insight into the cost of building and operating an unmanned ship.

The first is the Revolt project. This is a ship concept designed by DNV-GL, which investigates the possibility of an unmanned, battery powered ship. The concept study investigates a 100 TEU container vessel. The vessel is powered by a 3 MWh battery pack, making it not only autonomous, but also emission free. It is projected that the capital cost of the ship will be approximately €2.500.000 more expensive than a conventional ship of the same cargo capacity. However, it is also estimated that the yearly operating cost will be approximately € 825.000 lower [4]. In this project, no mention is made regarding the crew. A cost estimation of the technical changes is made. This cost estimation is set out against the crew cost to result in the estimated savings.

While the Revolt is a concept study, a similarly sized ship has been under development in Norway. Yara, a fertilizer company, and Kongsberg, teamed up to build the world's first autonomous, zero emission ship. As with the Revolt, the ship will be battery powered, with a battery pack of between 7 and 9 MWh [81]. The project, consisting of both research and development and the building of the ship, has received significant funding from the Norwegian Government and is estimated to cost between €25.000.000 and €30.000.000 [49, 88]. In 2020, the hull of the ship was delivered [91]. The cost estimations given have not been supported by published literature. They seem to have been solely based on the estimated technology costs, and savings due to the removal of the crew and the decreased building cost due to the removal of the accommodation.

Kretschmann et al. 2017 performed a comprehensive cost-benefit analysis on an unmanned autonomous bulk carrier. They stipulate that sailing without a crew lowers the operational cost not only due to the decrease in crew (and crew associated) cost, but also due to a reduction in weight and drag and therefore fuel consumption of the diesel engine. They estimate the reduction in fuel consumption to be 6%. The conclusions of this article are that removing the crew alone should be enough to cover the additional costs the ship incurs due to tasks being moved ashore. In this research, the focus is on changes to the operational profile of the ship to make it economically viable. The changes due to a lower drag and slow steaming are a key part of the economic calculations. The crew cost are mentioned, but the crew is removed as a whole, and no further investigation is performed.

From the estimated monetary benefits mentioned above, it is clear that the consensus is that sailing unmanned and autonomously will have a beneficial effect on the operating cost of the ship. In these estimations, a summation is made of the required technical innovations and their required cost, after which the crew cost are removed from the total cost. However, once again, it is unclear if the proposed solutions are enough to remove the crew from the ship entirely. Additionally, the cost estimations only focus on fully unmanned ships, and not on low manned ships. This means that there is no focus on the development path, only on the final solution. Since the transition from conventional ships to fully unmanned ships will not be instantaneous, the lack of knowledge about intermediate steps constitutes another important knowledge gap.

1.2.3. SOCIAL FEASIBILITY

Although societal, or social, feasibility is the final element, it is important to investigate if unmanned and autonomous ships have the possibility to become societally feasible before research into these ship types is performed. There are many parts of societal feasibility. For a technology to be fully integrated, it needs to be acceptable by the general public, as well as political and regulatory bodies.

Currently, unmanned and autonomous ships are not always looked upon favourably. People tend to see a lot of dangers with things they do not understand. Arguments are made that the ships could easily be hacked or that hijacking a vessel will become easier. Additionally, automating jobs that are now performed by people, brings up strong negative feelings. Even if there is a shortage now and many jobs will remain, but in a different setting.

The possibility of unmanned ships have spurred debates regarding many of the laws of the sea. For example; can an unmanned ship be classified as a ship under today's regulations [29]. The rules that govern ships are set by a number of different legal entities, such as the flag state and the IMO but also the port authorities. The minimum required size of the crew is governed by the Flag State of the ship. Many flag states, such as Panama [61], the Marshall Islands [51] and the Netherlands [58] follow the IMO Principles of Minimum Safe Manning Requirements for Vessels. This document states that a ship must have enough crew on board to perform the crucial tasks on board. It is up to the ship owner to prove that this is the case. It is then up to the Flag State to accept or reject the proposed manning plan for a ship.

This means that with regards to manning, there is no hard law that prevents the crew size from being reduced. However, there are several articles within the IMO principle of safe manning that assume crew members are on board. For example, the crew should be large enough to maintain watches at all times, moor and unmoor the ship, perform the required operations and be able to operate the Ship's Security Plan.

The classification societies are working on rules for unmanned ships [12, 46] Lloyds Register, 2017). Currently, the rules are still very open and general. However, the fact that these rules exist means that the classification societies are open to the possibility of unmanned ships, and are likely willing to adapt to new insights. Additionally the International Maritime Organisation has organised a scoping exercise with industry experts to identify how to best regulate unmanned and autonomous ships. These initiatives show that no showstoppers for unmanned and autonomous ships are expected.

1.3. Research Gap

From the literature above, a few observations can be made:

- There is a lot of research into individual technical solutions.
- There is no focus on the task and function of crew members and the relation between their tasks and the proposed technical solutions.
- In many cases the assumption is made that unmanned or autonomous ships will be economically feasible. However, there is only one article that goes into details and provides calculations to base their claim on [43].
- The research focusses on fully autonomous and remote controlled solutions. There is no research on reduced manning solutions.

This means that there is a lot of research into individual solutions, and even into combining multiple individual solutions into a full design. However, in these full designs it is unclear if the proposed technical additions cover all the tasks that the removed crew performs. Additionally, the research focusses on taking one step from a conventional ship towards a unmanned ship, without looking at the development path in between.

The key assumption on which this research is based, is that the tasks the crew performs now are a necessary part of the operation of the ship. In order to negate the role of the different crew members on board, one must first understand what role each crew member has in the fulfilment of the functions of a ship. Research into autonomous navigation, robust propulsion and communication between unmanned and manned ships are vital for the success of the unmanned ship. However, it is currently unknown what effect replacing these functions will have on the size and composition of the crew on board and, therefore, on the potential savings that they will bring.

The second key assumption made in this research is that there will likely be intermediate steps between the current situation and unmanned and autonomous ships. This research aims to identify several intermediate steps that are both technically feasible and economically feasible. This thesis will present the following:

- A task based design process which allows for the identification of feasible and viable ship and manning concepts for low manned and unmanned ships
- A Crew Analysis Algorithm that allows for the determination of a required crew for a given workload
- An economic viability study of selected promising concepts
- A case study that investigates the validity of the presented method
- A generalisation of the results towards a larger part of the fleet

1.4. RESEARCH QUESTIONS

This section introduces the research goal as well as the different questions that are answered over the course of this thesis to reach the research goal. After that, additional information is given about how each of the questions will be answered, and what the expected results will look like. The goal of this research is as follows:

To identify technically feasible and economically viable ship and manning concepts that are on the likely development path towards unmanned ships.

1. What is the role of the crew in the fulfilment of the functions of the ship? To ensure that all the tasks of the crew are replaced, all their tasks must first be investigated.
2. How can the effect of replacing crew tasks on the composition of the crew be determined? On board, each crew member has a set of tasks that they need to perform. When tasks or groups of tasks are removed, a new task distribution needs to be found. There are several mathematical approaches for solving these problems. An algorithm is set up to assign the tasks to suitable crew members.
3. What technically feasible options are available to replace crew tasks on board? After all tasks have been identified, the next step is to investigate possible replacement options.
4. What are the costs associated with these technically feasible options? To determine the economic feasibility of the proposed solutions, an estimation of the cost is required.
5. What ship and manning concepts are likely candidates for the development path towards unmanned ships? There are many conceivable intermediate steps between the conventional ship and the unmanned and autonomous ship. From these many options, a selection is made. To ensure that the selected concepts are economically viable, a cost-benefit analysis is performed.

1.4.1. DISSERTATION STRUCTURE

This section discusses how each of the research questions will be approached. Figure 1.3 shows a detailed overview of the design process that is introduced in this research to answer the research questions and reach the research goal.

As mentioned in the research gap, research hardly addresses the tasks that crew members perform on board. Answering the first question will shed light on this. To identify the role of the crew in the functions of the ship, the functions of the ship need to be determined first. The process by which this information is found can be found in the box denoted 'Ship specific information' in Figure 1.3. First, a functional breakdown analysis is performed. With the help of a field study and expert interviews the crew tasks are identified, using the functional breakdown of the ship as a basis. That way the first research question, what is the role of the crew in the fulfilment of the functions of the ship?, can be answered. This is discussed in chapter 2.

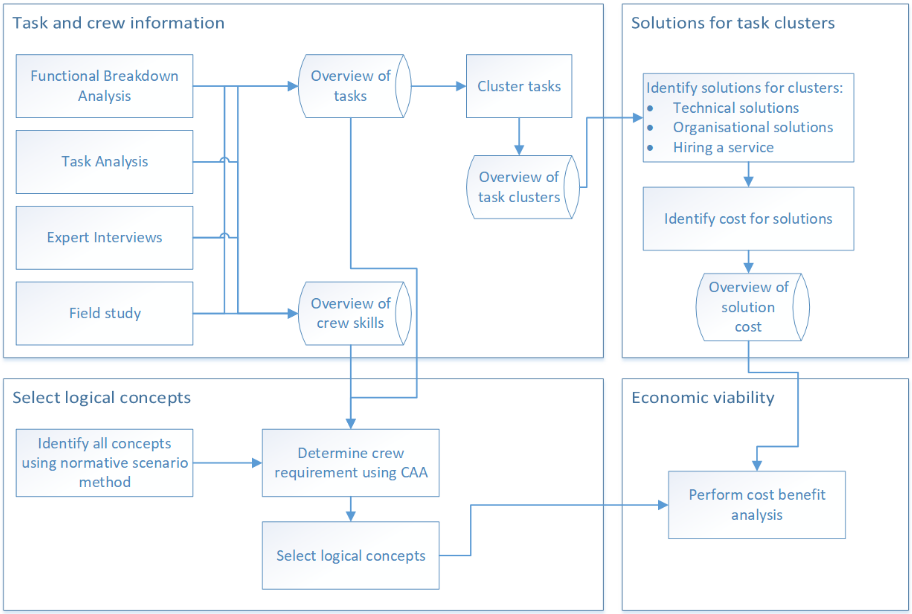


Figure 1.3: Overview of the design process introduced in this research showing the basic structure of the research

The next step is to find a way in which the effects of replacing the crew's tasks can be determined, as per research question 2. Task assignment problems, where tasks are distributed over actors who can perform them, are common mathematical challenges for which many different solution methods exist. Answering the second question means identifying which of the available solution methods allow for the analysis that needs to be performed in this research. When a method is selected, a crew analysis algorithm is set up using this method. This algorithm can calculate the required crew for a given set of tasks. The resulting design tool is an algorithm that can determine the cheapest crew given a specific workload. The possible solutions methods and the algorithm are discussed in chapter 3.

The next two questions, *what technically feasible options are available to replace crew tasks on board?*, and, *what are the costs associated with these technically feasible options?*, are closely related and will be discussed together. The process can be found in the box titled 'Solutions for clusters' in Figure 1 First, an assessment is made of the existing replacement solutions for the tasks found by answering the first research question. In part, this is done with the help of industry experts. The next step is to make an estimation of the cost of these solutions. This is discussed in chapter 4.

These cost assumptions are used to answer the final question, what ship and manning concepts are likely candidates for the development path towards unmanned ships? The crew analysis algorithm discussed in Chapter 3 can determine the required crew for any low-manned ship concept, given a specific input. A design method is set up that can assist with identifying which of the many generated concepts are worth investigating for their economic viability. The selected concepts are investigated for their economic viability by performing a basic cost-benefit analysis. The design method as well as the cost-benefit analyses can be found in chapter 5.

Overall, this thesis presents a structured design process to identify what changes are required to the ship and its organisational structure to reduce the number of crew members on board. This design process is applicable to all different ship types. In this dissertation, a short sea container vessel is used as a reference ship throughout each of the research elements discussed above. Adjustments will need to be made to satisfy the task requirements for the different ship types. There will be significant overlap between the tasks that are performed on different ships, but the tasks will not be exactly the same. However, each subsequent step is the same for the selected ship. In this thesis, a short sea container ship is used as a case study. At the end of this research a generalisation of the results is performed.

1.5. RESEARCH SCOPE

In the beginning stages of new technologies, there is generally no consensus on how a problem will be approached and solved. Many different companies and researchers will investigate a problem from their own standpoint, leading to many small entrepreneurial activities [26]. In the case of unmanned and autonomous ships, these entrepreneurial activities are expressed as research into the possibilities of sailing autonomously with different ship types. This dissertation cannot address all ship types, and therefore a suitable ship must be selected.

There has been a lot of research into unmanned and autonomous cargo ships, over a wide range of ship types, sizes, and cargo types. From small container vessels (<120 TEU), such as the Yara Birkeland and the Revolt [4, 36]) to an intercontinental bulk carrier investigated by the MUNIN project [69]. In addition to cargo vessels, ferries are mentioned as a good option for autonomous sailing (i.e., sailing without a specific navigation crew in this case). There are currently no ferries, or any other ship type, in operation; however, the Technical University of Trondheim are looking into a small ferry in the harbour of Trondheim [59]. Additionally, the SVAN project made use of a ferry to showcase their navigation system [71]. Finally, there are the ships that are used for tasks that are dangerous for the human operators. Firefighting ships [68], tugs [90] and naval ships [32, 54] have been mentioned as potentially benefitting from unmanned and autonomous sailing. In line with these ship types survey vessels and guard vessel would also be possible candidates.

In this thesis, a short sea container vessel is used as a continuous case study. This ship was selected for various reasons. The crew cost are relatively high, which means the benefit of sailing unmanned are likely to be bigger compared to ships where the crew cost is only a small fraction of the operational cost. Additionally, the ships generally sail short distances relatively close to shore. This means that maintenance can be performed often, and the should something go wrong, assistance can be provided quickly. Out of the cargo that short sea vessels carry, containers are the most laborious. They require the most interaction when being loaded and unloaded and require attention while the ship is out at sea. If solutions can be found for containers, it is assumed that solutions can also be found for other types of cargo. At the end of this thesis, a short assessment is made regarding the differences between the short sea container vessel and other ship types.

This analysis excludes an analysis of the role of the crew in case of catastrophic failures. The range of catastrophic failures that can happen on board of a ship is large, and the possibility of them occurring only small. Addressing them all in enough detail is not possible. Additionally, many of the procedures will likely change if the ship is low-manned or unmanned. This research focusses on the technological feasibility and economic viability of ships in their normal operating condition.

Currently regulations do not allow for unmanned sailing. There are many regulations that likely have to change to make this possible. There are many other rules and regulations that would need to change to allow for unmanned and autonomous ships. In this research, it is assumed that the regulations will change in due time, allowing for unmanned ships to set sail.

2

Functional and task analysis

To design an unmanned ship, one must first understand the role of the crew members in the operation of the ship. This chapter addresses the first research question posed in Chapter 1: *What is the role of the crew in the fulfilment of the functions of the ship?*

To answer this question, several steps are taken. The first is to perform a functional analysis to identify what the main functions of the ship are. For these functions, the human involvement can be determined.

2.1. Research methodology

This section introduces the method used to identify the functions of a ship and the tasks of the crew. Figure 2.1 shows the steps that are taken.

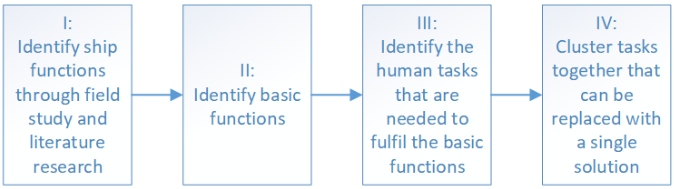


Figure 2.1: Overview of the research methodology presented in this chapter

2.1.1. The functional breakdown

The first step (Step I in Figure 2.1) in identifying the tasks performed by the crew is creating a functional breakdown of the ship. Based on the functions that the ship performs, it is possible to identify the tasks that are related to these functions. A functional breakdown structure is a systematic analysis of all the functions of a system [73]. It results in a

Parts of this chapter have been published in [41] full overview of all functions that a system, in this case a ship, must perform. The functional breakdown is created by analysing what functions need to be fulfilled for the ship to accomplish all operations such as move from one port to the next. This analysis is repeated until basic functions (i.e., functions that cannot be split further and can be performed by a single system or a person) can be found [83]. For this reason, the functional breakdown can also provide insight in the systems that are required to perform the basic functions. Known what kind of systems are involved can be helpful in determining how much time a specific task will take.

The functional breakdown will serve as a guide during a field study that is performed on board of the MV Endurance. Using the basic functions as a guide, the crew is interviewed about their tasks related to the completion of the different functions.

2.1.2. THE TASK BREAKDOWN

Many of the basic functions on board of a ship are generic and hold true for many different ship types and ship sizes. For example, navigation, mooring and maintenance of the equipment will have to be performed regardless of the ship type. However, the exact task distribution over crew members is dependent on many factors such as the ship's size, the ship owner, the cargo it carries and its operating equipment installed on board.

This research found no academic literature that focusses specifically on the tasks that are performed on board of ships. While there are training manuals available that provide details on how operations and procedures should take place these manuals provide limited academic insight into the distribution of tasks and the reasoning behind it.

To get insight into the tasks that differently ranked crew members perform on board in general and on board of short sea ships in specific, a field study was performed on board of the *MV Endurance*, a short sea container vessel that, at the time of the field study, sailed between Antwerp, Belgium and Belfast, Northern Ireland. The field study took place over one journey from Belfast to Antwerp in March 2018 and provided valuable insights into the number of tasks on board and the distribution of these tasks across the different crew members. The different crew members were shadowed and interviewed regarding their daily tasks and duties.

The crew of the *MV Endurance* consisted of 11 crew members, all of whom were asked questions regarding their tasks and responsibilities. The experience of the crew ranged from approximately one year for one of the deck boys to well over 20 years for the captain. Some had sailed on the ship for multiple years, while two others, the second officer and the chief officer, were on board for the first time for this trip. These two crew members had several years of experience as chief officer before switching to sailing on the *MV Endurance*.

After performing the field study several industry experts from the Dutch nautical schools were interviewed to generalise the list of tasks and duties. For the tasks of the bridge and deck crew, interviews were conducted with an educator from the Hogeschool

Rotterdam, who had multiple years of sailing experience before switching to teaching at the nautical school. A second interview was conducted with three teachers from nautical school Maritiem Instituut Willem Barentsz, during which the tasks of all departments were discussed. Two of these teachers had sailed as engineers on different types of ships.

EXPERT INTERVIEWS

There are many ways to conduct an interview and obtain the desired results. In this case, two distinct ways of interviewing experts were used. First, the crew on board were interviewed. The general goal of the field study, and the specific goal of the interviews was to gain a broad view of the on-board situation of the ship. The ultimate goal was to get a better picture of the skills and duties of each of the crew members. In literature, this type of interview is referred to as an exploratory interview. During an exploratory interview, the aim is to be as open as possible. This ensures that a lot of information is gathered [53]. During the field study this method was applied by first asking very open questions such as can you describe your duties on board or can you explain how a typical work day looks. To add to these more open ended questions, specific questions were asked for further clarification and details. The interviews took place over the three days that the voyage took, allowing also for observation and further questioning based on these observations. The crew of the MV Endurance provided detailed information and gaps were filled in with occasional directive questioning. The field study, in combination with these exploratory interviews resulted in a list of tasks, specific for the*MV Endurance*.

For a more general picture, several industry experts from Dutch nautical schools were interviewed. In these interviews the goals were different from the interviews conducted on board. Where the goal on board was to gain as much knowledge as possible, the goal of the second round of interviews was to fill in gaps and provide missing information. Interviews with this type of goal are referred to as systematizing interviews. During systematizing expert interviews the goal is to gain access to specific knowledge that the expert possesses [53]. This is usually based on information obtained from practice. In this case, each of the experts was presented with the list of tasks and information regarding the workload and the crew members involved. Questions focussed mainly on the details of the tasks. At the end of the interviews, each expert was asked to add any missing tasks to the list.

Interviewing experts in this manner has resulted in a list of tasks and skills that are applicable to short sea container vessels. Many of the tasks found apply to more ships than only the short sea container vessels. Tasks that cover, for example, maintenance and navigation will be very similar regardless of the ship type. However, there are also tasks that differ between ship types such as the conditioning of the cargo. Finally, there can be differences in how the tasks are distributed over crew members. For example, medical care could be assigned to a crew member with a different rank, or specific maintenance could be assigned to a specific crew member. Additionally, a larger crew might also mean a different distribution of tasks. While many things remain the same, a check on the tasks and skills of the crew members should be performed for every new ship analysed using the method presented in this thesis.

2.2. THE MAIN FUNCTIONS OF A CONTAINER VESSEL

Step II in Figure 2.1 mentions the identification of the basic functions. In Watson's classic approach [87], it is stated that in warship design there are three main functions that designers must keep in mind when designing a ship: to float, to move and to fight. However, in this case the ship in question is a container vessel. The definition of *to fight* is broad, even if only looking at the definition of a war ship. Therefore, this research redefines the function *to fight* as *to perform the ship's mission*. In case of the container vessel that would be to transport the containers A to B. Secondarily, the ship must transport its crew safely from A to B as well. Once the crew is removed from the ship, this secondary function is no longer required.

During the course of making the functional breakdown, it was found that in addition to these three functions, two additional functions play an important role in the operation of the ship. The first is communication. This is a part of almost every function the ship can perform, from communication between two ships to the communication from a sensor to a computer. This aspect is key in conventional shipping, but just as important in unmanned and autonomous shipping. Currently crew members play a key role in communication. For unmanned ships this is no longer possible, which means very clear new communication pathways need to be defined. To better identify the different communication types, communication is added as a main function. It was also found that the three main functions identified by Watson do not cover what happens in case of failure. This is an important area for autonomous ships, since the crew is now the first line of defence in many cases. Therefore, it is important to know how failures are prevented or currently solved, what systems exist to prevent or mitigate these failures, and what role the crew plays. For this reason the function *prevent and mitigate failure* is also added as a main function. This function is discussed in this chapter, but as stated in the introduction, will be left out of scope for the rest of the research.

To summarize, the main functions of a ship are identified as:

- Float
- Move
- Perform mission (i.e., transport containers and crew)
- Communicate
- Prevent and mitigate failure

The main functions and their first order sub-functions of a generic container vessel can be found in Figure 2.2. Below, a short explanation of each of the main functions is given, as well as a more detailed overview of the main functions in the following sections

2.2.1. TO FLOAT

The function to float covers the sub functions; to have structural integrity, to be watertight and to provide displacement. The involvement of the crew mainly consists of maintenance tasks to ensure that the hull of the ship remains in good condition to provide these functions.

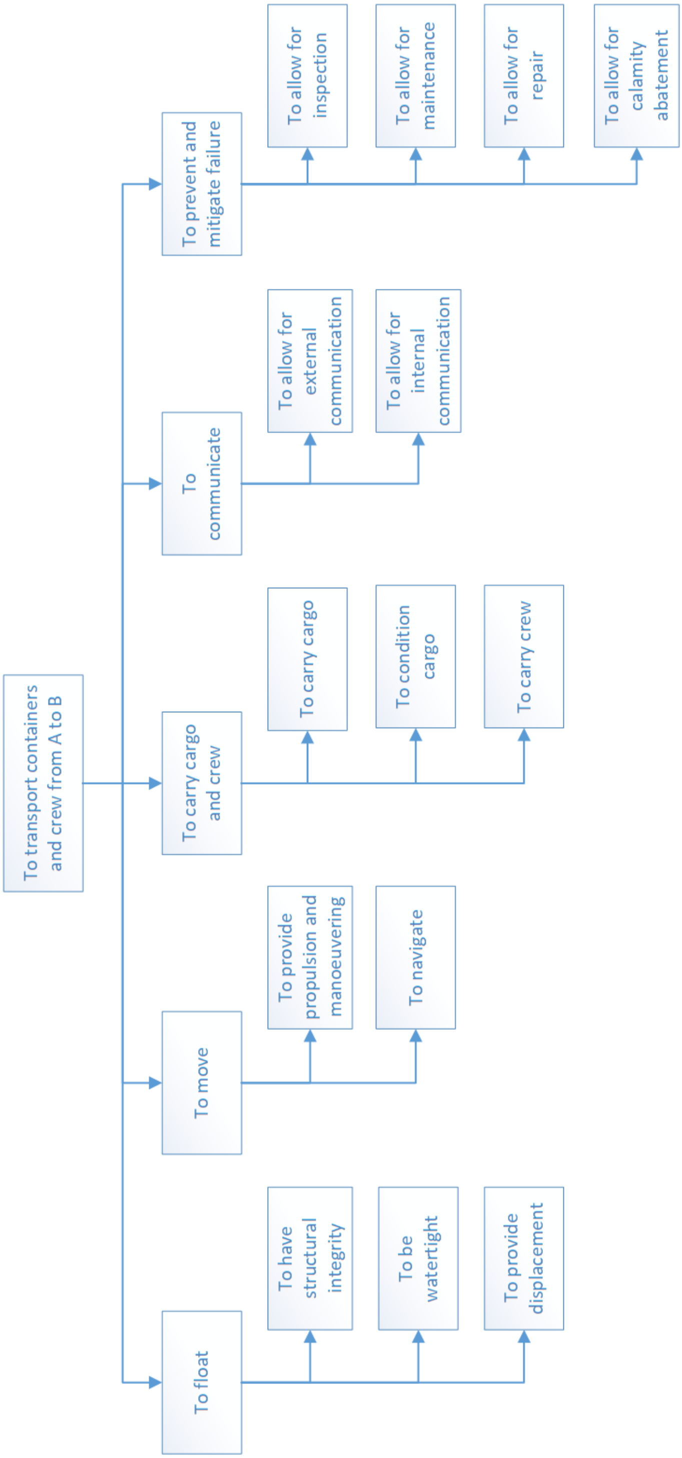


Figure 2.2: Overview of the main functions and first order sub functions of a short sea container vessel

2.2.2. To move

The function *to move* not only covers the physical movement of the ship, but also the planning of this movement, i.e., navigation (see Figure 2.3). The physical moving of the ship consists of functions covering the movement of the ship in all directions, for example, proving lateral thrust at slow speeds, or providing longitudinal thrust. The navigational part of the to move function mostly consist of planning the route and being able to follow it without any problems. Many of these functions require human interaction or are even performed by crew members almost exclusively. For example, during the mooring process, the steering is done by hand by the captain, and multiple crew members are involved in ensuring that the mooring lines are passed to shore. On the other hand, the navigation of the ship can be done almost completely by the installed systems, by the form of way-point following. However, even in that case, a crew member has to keep watch at all times.

2.2.3. To perform the ship's mission

The function to perform the ship's mission is the key function of all commercial cargo ships. For the short sea container vessels investigated in this research, it includes the ability to load and unload cargo and safely carry the cargo to the next port. It also includes all elements that are required for safe and comfortable passage of the crew, such as providing HVAC and electricity. The cargo on board is not simply loaded and not looked at again. The vibrations of the ship can cause the lashings of the containers to loosen, causing them to potentially fall overboard. To that end, crew members are tasked with tightening the lashings of the containers intermittently. Along those same lines, crew members also regularly check if the refrigeration containers are still operational and can perform maintenance if this is not the case. The full breakdown can be found in Figure 2.4.

2.2.4. To communicate

There are several forms of communication that take place during a mission. There is internal communication between systems and between crewmembers, external communication with the shore (e.g., the vessel owner, port authorities, and terminals) and communication between ships. Additionally the ship is able to send out several different emergency signals. Internally the most used methods of communication are verbal communication between crew and data transfer between systems. Finally the systems also communicate with the crew, for example by showing data on a screen or giving alarms. In external communication verbal communication and data transfer are also important, while additional communication happens via lights and sound signals. Each of these manners of communication takes place in both ship-to-ship and ship-to-shore. The full breakdown is shown in Figure 2.5.

2.2.5. To prevent and mitigate failure

The final main function of the ship is the ability to solve problems if something breaks down as well as to do maintenance to decrease the possibility of a failure. This is a very broad function as it covers many potential problems that can occur on board of a ship. In general it covers the ability of each system and space to be inspected, maintained and be

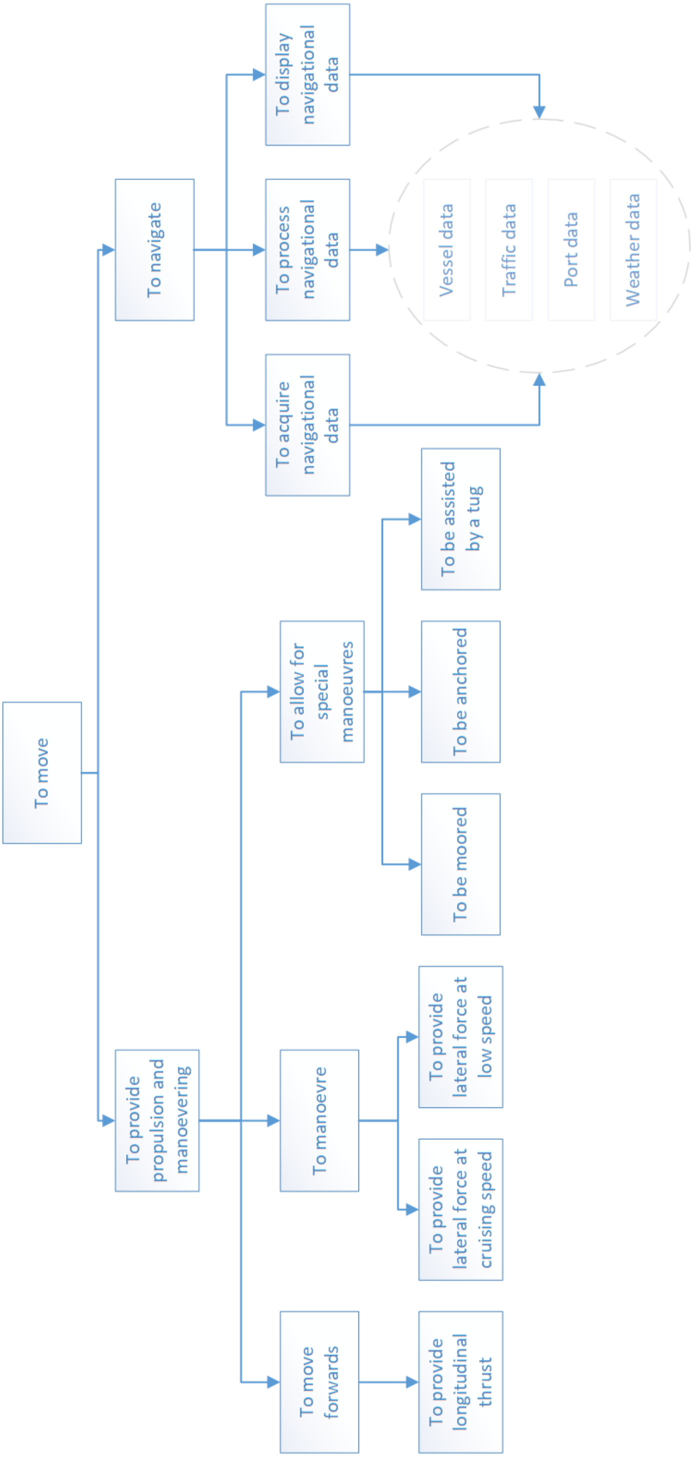


Figure 2.3: Complete overview of the main function to move

2

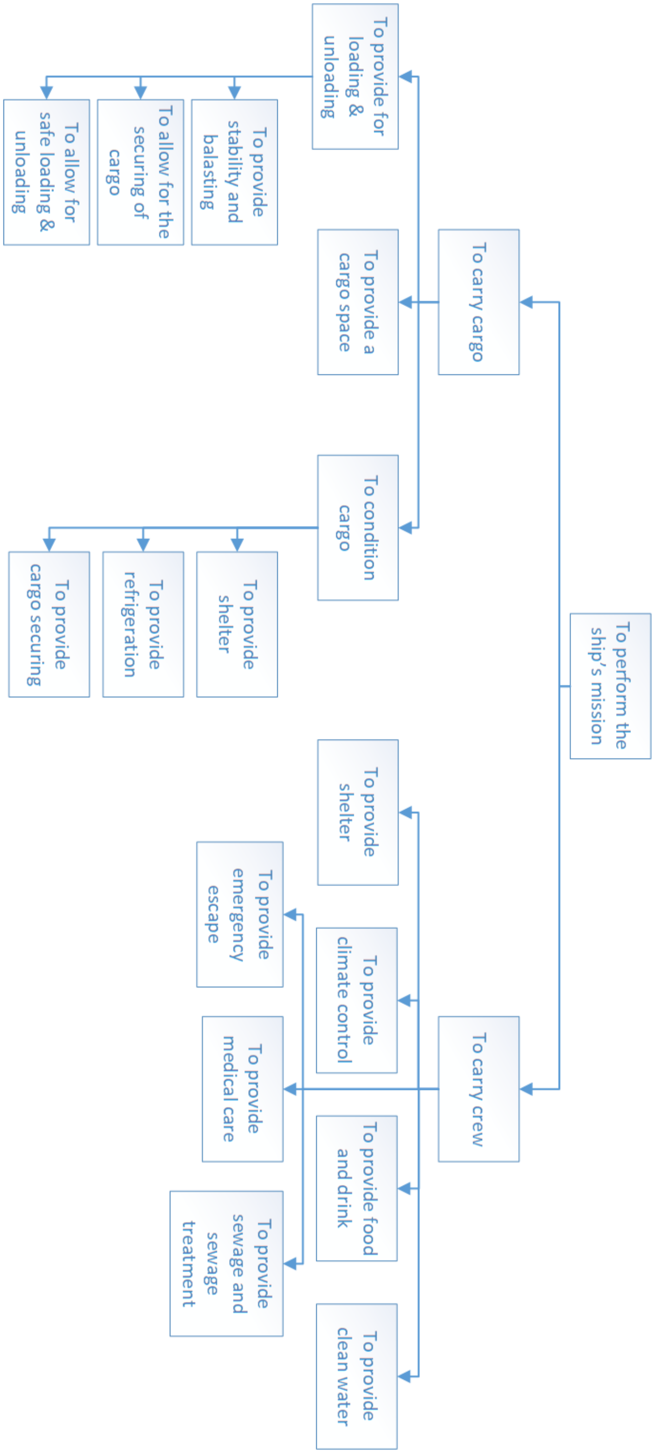


Figure 2.4: Overview of the main function to perform the ship's mission

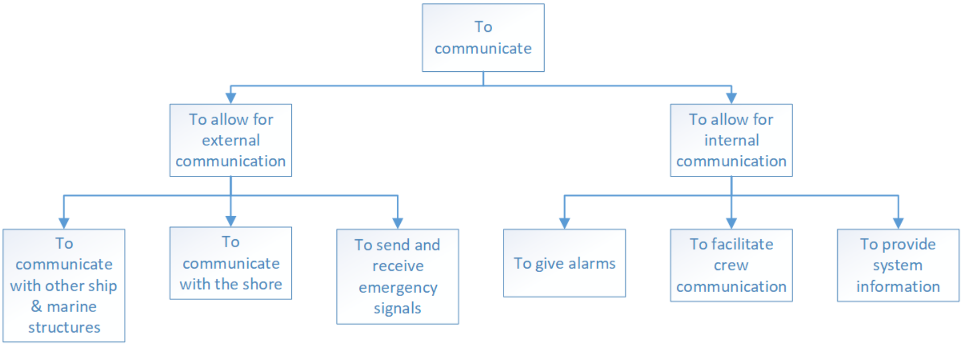


Figure 2.5: Overview of the main function to communicate

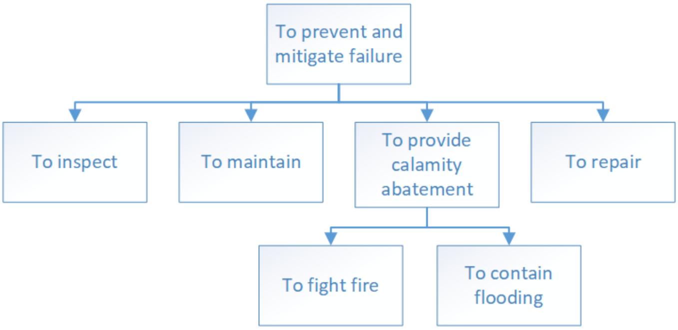


Figure 2.6: Overview of the main function to prevent and mitigate failure

repaired if required as well as calamity abatement. A significant portion of the maintenance to the ship is performed while out at sea. Only maintenance that required special equipment or additional personnel to be performed is done while in port. The ship is rarely taken out of commission to perform additional maintenance. The largest portion of the maintenance work is performed in the engine room, where crew members work to keep the main engine and its associated systems in good condition. Other maintenance work is performed on deck equipment such as the mooring and anchor winches. The full breakdown can be found in Figure 2.6.

2.3. THE TASK BREAKDOWN

The field study that provided input for the functional breakdown, also provided insight to the tasks and skills of each of the different crew members on board of the ship. This is step III in Figure 2.1. As explained above in Section 2.1.2, the crew members were interviewed and asked about their roles in the fulfilment of the functions and their training. However, this is the situation on board of one ship, which might not represent the situation in general. To get a more generalised picture of the task distribution on board, several industry experts from the Dutch nautical schools were interviewed to give their input. The way that tasks are distributed are governed by rules and regulations as well as traditions. That means that there were not that many differences between the tasks that needed to be performed. However, dependent on the ship's size, age, route and operator, tasks may be given more or less hours or crew members. Additionally, having a slightly different crew on board, might also change which task is assigned to which crew member. Therefore, this analysis is not usable for every ship, but most of the tasks that were identified will be performed on any given ship.

2.3.1. THE TASK LIST

This method resulted in a list of tasks that are performed during the journey of a ship. Although a very large number of small subtasks have to be performed on board, many of these tasks can be clustered into larger tasks. For these larger tasks the workload and required man-hours can be estimated more reliably. Therefore, this research uses a bottom up approach, where the smaller tasks are grouped together to form a larger task. For example; in the engine room the engineers perform planned maintenance as well as repairs on a wide variety of equipment. Instead of placing all small tasks on the task list, the tasks are grouped into two large tasks: *maintenance in the engine room* and *repairs in the engine room*. This clustering of subtasks prevents an analysis of the effects of small automation measures for individual subtasks, but the selected aggregation level is suitable to assess the impact of larger automation options such as automated mooring or autonomous navigation. Automating only a small task of a crew members workload (e.g., the maintenance of a specific system) will lighten their workload but will not achieve the removal of that crew member from board. Clustering the tasks allows for a balance between the number of tasks investigated and the ultimate goal of removing all crew members. The process of combining tasks has resulted in a list of 34 tasks which can be found in Table 2.1.

In Figure 2.1 it is state that the final step performed in this chapter is to cluster the tasks together. To group the tasks together, an investigation is performed to find existing (technical) solutions and proposed solutions for (parts of) the unmanned shipping challenge that can be found in literature. Many of the proposed solutions are discussed in Chapter 4. Logical reasoning then allowed for the grouping of the 33 identified tasks. Next, a group of industry experts from different backgrounds and levels of experience, ranging from inland shipping to yacht design and teachers at the naval academies were asked group the tasks together as well to verify the findings. The 10 clusters that were found can also be found in Table 2.1.

2.4. DIFFERENT TRAVEL PHASES

The field study highlighted that a ship encounters three distinct phases during a round trip. Each of these phases has different functions for the ship to perform as well as rules and regulations that govern these functions. These phases are; the loading and unloading phase, the arrival and departure phase and the normal sailing phase. Each of the three travel phases consist of very different tasks, and are governed by different regulations. Additionally, the three travel phases have different crew requirements. For those reasons, the three travel phases are used for the rest of this research. Table 2.2 shows

Table 2.1: List of tasks and their logical grouping according to industry experts

No	Cluster	Tasks involved
1	Mooring	Preparing bridge for arrival and departure Preparing engine room for arrival and departure Watch keeping in engine room during arrival and departure Handling of mooring lines Supervise preparations of deck for arrival and departure Prepare deck for arrival and departure Clear up deck after arrival and departure
2	Navigation	Watch keeping during arrival and departure Watch keeping during normal sailing Additional watch keeping at night during normal sailing Manoeuvring the ship during arrival and departure
3	Maintenance in engine room	Maintenance in engine room during loading and unloading Maintenance in engine room during normal sailing Maintenance paperwork during loading and unloading Maintenance paperwork during normal sailing Night watch in engine room during normal sailing Repair in engine room during normal sailing
4	Maintenance on deck	Perform maintenance and repair of emergency equipment Check refrigerated containers twice daily Perform maintenance of superstructure and hull Maintain hatch covers
5	Bunkering	Supervise bunkering of fuel Disposal of oil waste Supervise bunkering of lubrication oil
6	Administration	Perform administrative duties during loading and unloading Perform administrative duties during normal sailing Work planning
7	Port supervision	Port watch: cargo loading and unloading supervision Port watch: Access control
8	Responsibility	Responsibility in the engine room Responsibility for the ship
9	Cargo conditioning	Perform cargo conditioning (securing containers)
10	Crew support	Prepare food and drink Provide medical care and maintain medical equipment

which clusters take place in each of the travel phases.

Table 2.2: Overview of clusters that take place in each of the travel phases

Loading and unloading	Arrival and departure	Normal sailing
Maintenance in the engine room	Mooring	Navigation
Bunkering	Navigation	Maintenance in the engine room
Administration	Maintenance in the engine room	Maintenance on deck
Port supervision	Responsibility	Administration
Responsibility		Responsibility
Life support		Cargo conditioning
		Life support

The loading and unloading phase takes place while the ship is moored at a quay. During this phase, a lot of time is spent on the cargo handling. Additionally, the ship is refuelled, stores are replaced, maintenance that cannot be done at sea is performed and all the paperwork for the next journey is prepared. This is the phase during which most contact with external personnel is possible and during which external personnel is on board.

During the arrival and departure phase, the ship sails in shallow, narrow and/or busy waters or within a port until it reaches open sea. Sailing in these waters means that some additional safety measures are required. For example, an engineer needs to be present in the engine room at all times. This ensures that there is always someone nearby in case of failure. During normal sailing, the engineers can leave the engine room unattended for several hours at the time given that an alarm is set. This is not possible during arrival and departure. Additionally, this phase includes the mooring and unmooring of the ship.

The normal sailing phase is the longest phase of a voyage which takes place while the ship is at open sea. During this phase, the main task of the bridge crew is navigating the ship, which takes up most of their workday. Additionally they perform administrative duties, work planning and they are responsible for the medical care on board. The engineering department spend most of their time performing routine maintenance and some repairs. The deck department performs general maintenance of the superstructure and hull and takes care of the cargo. The distribution of work is highly dependent on factors such as the weather. During bad weather, maintenance and cleaning are performed inside to ensure the safety of the crew.

There are some functions that the ship needs to fulfil in multiple travel phases. For example, the sub function *to manoeuvre* takes place both in the normal sailing and in the arrival and departure phase. However, the skill required for the crew member performing the task belonging to this function differs. Navigating a busy, narrow and/or shallow waterway requires significantly more skill than sailing in open waters. Using these three distinct phases makes it easier to identify all tasks that are performed on board of the ship. However, knowing which tasks are performed is not the only thing required to investigate how to replace all the crew members on board. For this, it is also important to know which crew members perform which tasks and what their skills are in performing these tasks. How this was investigated is discussed in Chapter 3.

2.5. CHAPTER SUMMARY

This question answers the first research question; *What is the role of the crew in the fulfilment of the fucntions of the ship*. To that end, the following process is set up. First a functional breakdown and a task breakdown are made. The 5 main functions of a ship; to float, to move, to perform the ship‘s mission, to communicate and to prevent and mitigate failures are investigated down to their basic functions. From the basic functions, the involvement of the crew in fulfilling these functions can be investigated through a field study and with the help of industry experts. This results in a list of tasks that are currently performed by the crew, divided over three travel phases. The tasks are clustered together in such a way that the clusters can be replaced by one solution.

The method described above is applied to a short sea container vessel. For this ship, the method resulted in 34 tasks. These tasks were combined into 10 clusters of tasks. The task breakdown, and the corresponding clusters, will be a key part of the input for the analysis algorithm that is set up in the next chapter. This algorithm will be used to determine the effects that task replacement options have on the size and composition of the crew.

3

THE CREW ANALYSIS ALGORITHM

IN the previous chapter, an analysis of the current manning situation was made by identifying the tasks that each crew member performs. This list of tasks is a key input in answering the second research question: *how can the effect of replacing tasks on the composition of the crew be determined?*

In this thesis there is a given workload on board for which a suitable crew must be found. For the manning of the ship, there are different crew members available, each with a certain set of skills. On the other hand, there is a list of tasks that needs to be performed by a certain number of people with the skill to perform that task. The tasks on board of a merchant ship are rather predictable and flexible. Tasks are often schedueled at a time that suits the ship best. Additionally, the grouping of small tasks under the umbrella of a larger task takes the requirement of schedueling tasks out of the equation completely.

Problems such as this are common in operations research and are referred to as assignment problems [27]. A set of agents (in this case crew members) is available to perform a set of tasks. The goal is to find a distribution of the tasks over the selected crew members. In this case the distribution should be such that the crew cost are as low as possible.

There are many different ways to solve an assignment problem, depending on the result that the user wishes to achieve. This chapter first discusses several ways to solve an assignment problem and the preferred method for this research is selected. Next, the algorithm that is developed to solve the assignment problem of this thesis is explained. Finally, a case study is performed to show how the algorithm works in more detail in which the navigation tasks of the short sea container vessel are presumed to be automated.

Parts of this chapter have been published in [39] and [40]

3.1. THEORY

There are several mathematical methods available to solve an assignment problem. However, before the solution methods are investigated, the problem needs to be defined in more detail. In short, there is a list of tasks that needs to be performed by a set of crew members. Not all crew members can perform all tasks. Each crew member has a specific skill set that needs to be matched to the tasks. The tasks themselves have their own requirements, e.g., the number of crew members required and the required hours per crew member, in addition to a skill level. They each have a duration, that needs to fit the available work hours of the crew members. These are the constraints for the algorithm. The clusters that have been identified in Chapter 2 are not dependent on each other. In this case, dependent means that the clusters do not have to be performed in a specific order or simultaniously. Therefore, the algorithm does not need to perform detailed, time dependent scheduling (i.e., it is not important to know what task the captain will be doing on Tuesday at 13:15).

Mathematically, an assignment problem can be defined if it satisfies the following 5 assumptions [27, p. 348].

1. There are n assignees and n tasks, which creates a square matrix for the problem
2. Each assignee is assigned exactly one task
3. Each task is performed by exactly one assignee
4. There is a cost associated to each assignee performing each specific task
5. The object of the algorithm is to minimise the cost of completing all tasks.

The 4$^{\text{th}}$ and 5$^{\text{th}}$ assumptions are easily met by the problem outlined above. The ultimate goal of the algorithm is to determine the cheapest crew that can perform a set of tasks (satisfying assumption 5). Additionally, each crew member has a different cost, and thus there is a different cost associated to each crew member performing a task (satisfying assumption 4). The other three assumptions are less obvious but can be met by assuming that the assignees and the tasks are not crew members and full tasks but 1 hour blocks. The working hours of a crew member are divided in hour long blocks to make up the assignees and the tasks identified in Chapter 2 are also split into blocks of 1 hour. In that way assumption 2 and 3 are met.

This way of defining the problem means that automatically assumption 1 can also be met, given that there is an equal number of crew hours and task hours available. This is not the case for this problem, as the program could potentially select any number of crew members and assign them all 1 hour, leaving the rest of their available hours unassigned. Additionally, the workload on board does not necessarily match up to the available hours of the crew members on board, especially not when tasks are replaced to achieve a smaller crew. To this end, dummy tasks can be created to create a square $n \, x \, n$ matrix. Dummy tasks are tasks that have no hours, no skill requirement and no associated cost. Their function is merely to support the possibility of using matrix operations to solve the assignment problems, and therefore do not influence the results in any way.

How the assignment of tasks and the use of dummy tasks work can be explained in a small example. Imagine two crew members that each have 3 hours available and four tasks (A,B,C and D) that each take one hour. For simplicity, each crew member can perform each task and the cost of each crew member is the same. In 3.1 the distribution of the tasks over the crew members is shown. As explained, each of the crew members is split into parts of one hour, allowing for each task of one hour to be assigned to one (part of) crew member. The result is that crew member 1 performs tasks A,B and C and has a workload of 3 hours. Crew member 2 performs task D and has a workload of 1 hour.

Task	Crew member 1			Crew member 2		
	1.1	1.2	1.3	2.1	2.2	2.3
A	X					
B		X				
C			X			
D				X		
Dummy task 1					X	
Dummy task 2						X

Figure 3.1: Basic explanation of the use of dummy tasks

3.1.1. MATHEMATICAL DEFINITION OF THE ASSIGNMENT PROBLEM

Mathematically, an assignment problem is defined as:

$$\min C = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij}$$

Subject to:

$$\sum_{i=1}^{n} x_{ij} = 1 \qquad \text{for i = 1,2...n} \tag{3.1}$$

$$\sum_{j=1}^{n} x_{ij} = 1 \qquad \text{for i = 1,2...n} \tag{3.2}$$

And

$$x_{ij} \geqslant 1 \qquad \text{for all i and j} \tag{3.3}$$

$$x_{ij} \text{ is binary} \qquad \text{for all i and j} \tag{3.4}$$

In which C is the total cost of performing all the tasks, c_{ij} is the individual cost of performing a task and x_{ij} is a binary variable that represents whether or not a specific task is assigned to a specific assignees (i.e., a one hour fraction of a crew member's work day). The first two constraints stipulate that each task can only be assigned once, and that each crew member can only perform one task.

The mathematical representation above is general and applies to any assignment problem. To specify the problem, constraints are required. For almost any assignment problem, there are many constraints, for example regarding which actor can perform which task. Therefore, it is customary to provide the cost matrix as it gives all constraints for the problem. The cost matrix takes the shape as is shown in Table 3.1.

Table 3.1: Example cost matrix for an assignment problem with n actors and n tasks

		Tasks				
		1	**2**	**...**	**n**	**Supply**
Actors	**1**	C_{11}	C_{12}	...	C_{1n}	1
	2	C_{21}	$C22$	...	C_{2n}	1
	...	...	...	...	...	...
	n	C_{n1}	C_{n2}	...	C_{nn}	1
	Demand	1	1	...	1	

For the assignment problem in this research, the cost of performing a task (in this case defined as the monthly cost of hiring that specific crew member) can be added to each task that the crew member can perform. This results in the specific cost matrix for this problem. The cost matrix for this problem is significantly large and will not be presented here. However, the input that is used to set up the cost matrix is discussed below.

3.1.2. SOLVING AN ASSIGNMENT PROBLEM

This section investigates different methods to solve assignment problems. First, the different solution methods are investigated, after which a selection is made. There is a wide range of solution possibilities, dependent mostly on the complexity of the problem.

To select a method, the following requirements have been set up:

- The method must have a fast lead time (i.e., seconds).
- Scheduling of the tasks within a travel phase over time is not required. The only interest is in who performs what task, not when.
- The method must be verifiable, either by hand or by a calculation method.
- The method must fit with the identified goal (i.e., find the cheapest crew) and not be more complicated than required.

Reyes et al. [65] give a comprehensive and detailed overview of the many different solution methods for a storage location assignment problem, a specific type of assignment problem. In a storage location assignment problem there are differently sized packages that must be placed at different locations. The goal is to minimize both the use of the space and the cost of material handling. In other words, it costs a certain amount of money to place a certain package in a certain location, just like it costs a certain amount of money to have a certain task be performed by a certain crew member. Constraints can be placed on the placement of packages, like constraints are placed on the assignment of tasks to crew members. For that reason, the methods suggested for the solution of the storage location assignment problem can be used for the assignment problem in this research as well.[65] introduces groups of solution methods are introduced, of which 4 are generally applicable:

- Extact methods rn
- Heuristic methods
- Meta heuristic methods
- Simulation

EXACT METHODS

Exact methods include methods such as mixed integer linear programming (MILP), binary programming, non-linear programming, Pareto borders and the branch and bound method [65]. In general, the exact methods are complex. In research, the calculation model or algorithm is generally introduced but not applied to an actual problem due to its complexity [65]. The methods can be used for small problems, but are difficult to scale up to larger problems.

HEURISTIC METHODS

Heuristic models are generally very good at quickly solving large problems. However, there is a risk of not finding the global optimum but the local optimum instead. An example of a heuristic method is the greedy algorithm [27]. A greedy algorithm works by making logical, opportunistic, choices. For example, assume a selection of euro coins, with a value of 1,2,5 and 10 cents. The goal of the algorithm is to find the smallest combination of coins that makes 17. A greedy algorithm could be set up in such a way that the largest coin that does not exceed the goal value is selected at all times. In that case, the following steps would be taken:

- Select a coin of value 10, making a total of 10 cents
- Select a coin of value 5, as 10 cents exceeds the goal value, making a total of 15 cents
- Select a coin of value 2, leading to the goal value of 17 cents

As the algorithm is based on oportunistic and logical choices made in each step, the implementation time is relatively short [76]. The programming of these steps is relatively simple and easy to plan, cutting down on the implementation time. This also means that the runtime of the algorithm is very short (i.e., seconds) as the algorithm does not compute all the effects of many possible steps. This logic-based decision process is also the downside of a greedy algorithm. It looks for local optima in the hope of finding the global optimum, which it does not achieve for every problem [76].

To illustrate this, lets once again assume a selection of coins. In this case of a value of 1, 8 and 10 cents but with the same goal of achieving a combined value of 17 cents. Using the same algorithm as before would result in the algorithm selecting the following coins: 10, 1, 1, 1, 1, 1, 1, 1. This is a correct solution, however, it is not the optimal solution. This would be 8, 8, 1, which results in requiring 5 coins less. This illustrates the biggest weakness of a greedy algorithm, ending in a local instead of a global optimum.

The benefits of the greedy algorithm are that it is easy to implement and that the calculation time is generally very quick. Additionally, the steps of the algorithm are based on logic and are therefore easy to follow and to correct if necessary.

Meta heuristic methods

Metaheuristic methods are general solution methods that give a general structure and guidelines for setting up a heuristic method to solve a problem [27]. Using a metaheuristic method ensures that setting up a heuristic method for every new problem is not required. Some of the well-known metaheuristic methods are the tabu-search, a genetic algorithm and simulated annealing. All three of the methods aim to improve the chance that the solution of the problem is a global optimum, instead of a local optimum.

When using a tabu-search, a random solution is used as a starting point. From that starting point, neighboring solutions are investigated. To ensure that the algorithm does not return to its starting point, a tabu-list is used. This tabu-list contains a number of changes that have been made to the solution that cannot be reversed unless no better solution is found. The process is repeated until the termination condition (e.g., a number of iterations or a solution below a certain value) are reached [27, 75].

Simulated annealing simulates the scientific process of annealing and is similar to a tabu-search but with a specific way of investigating new solutions. From the current solution, a random neighbour is selected. If the outcome of this solution is better than the previous solution, it is automatically accepted. If the solution is not better, a probability of acceptance is calculated and compared to a random number. This means that worse solutions can always be accepted, ensuring that the local optimum can be escaped [27, 75].

A genetic algorithm is effective in investigating the feasible region of a problem while slowly finding its way to the optimal solution. As the name suggests, the idea for this algorithm comes from biology. To start, multiple random solutions are generated, called a population. These solutions make up the first generation. By combining traits from two “parent” solutions, a second generation can be created. The fittest members are selected, making up a new generation with the same size of the previous one. This process is repeated until a termination condition is met [27, 75].

In shipping, these methods are used frequently. However, these methods are used mainly for routing and scheduling problems of ships, not for the determination of required crew members on board. In much of the research, scheduling plays a big role in the problem that is solved. For example; Al-Hamad et al. [22] use a genetic algorithm to look into a routing and scheduling problem for multiple ships, Wang et. al [84] use a tabu search to look into a scheduling problem with speed optimization and Kosmas and Vlachos [42] use simulated annealing to solve a routing problem.

Simulation

Simulation is a method that has been used repeatedly in maritime assignment problems. In the maritime industry, most of the research on optimised manning has been performed for naval ships (e.g., [3, 17, 89]). Alapetite and Kozine [2] looked into the safe manning of merchant ships. Most of these studies apply a variation of network simulation modelling, and more specifically discrete event simulation (DES), to solve the problem.

In discrete event simulation, changes to the situation do not happen gradually (i.e., continuous simulation) but at once at a random interval. A common example of discrete event simulation is a queuing problem where customers show up at different moments in time. Translating this to an assignment problem means that DES allows for the use of an inter-arrival time between different tasks, changes in the probability distribution of task length [2], and the use of time sensitive tasks that are dependent on each other [18].

However, these attributes are applicable in procedures that require tasks to be performed in a specific order and/or at a specific time. This is not the case for tasks on board of a merchant vessel. The tasks on board of merchant vessels are not dependent on each other directly (i.e., not part of a specific sequence) as long as the distinction in travel phases from Chapter 2 is made. This also means that the tasks are less time sensitive.

3.1.3. METHOD SELECTION

In Section 3.1.2, the selection criteria for the method were identified.

- The method must have a fast lead time (i.e., seconds).
- Scheduling of the tasks within a travel phase over time is not required. The only interest is in who performs what task, not when.
- The method must be verifiable, either by hand or by a calculation method.
- The method must fit with the identified goal (i.e., find the cheapest crew) and not be more complicated than required.

Based on the first and fourth criterium, the exact methods are not selected. The exact methods require complicated calculations and code. Additionally, they are not applied in practice. Together, this means that the exact methods are not suitable for what is required in this case. The simulation methods are not selected due to the second and fourth constraint. Techniques such as DES are possible, however adding a scheduling component to the solution that is not required here.

This leaves the meta-heuristic methods and heuristic methods. Both approaches are capable of solving the problem and meet the requirements stated above. This means that the selection of the method needs to be made based on how well each method fulfills the requirements. Both heuristics and meta-heuristic methods have a fast lead time. Out of the options suggested above, the greedy algorithm is the fastest, due to the limited number of options that are considered in the assignment problem. None of the methods are used for scheduelling nor are they overly complicated due to the addition of unrequired additional information. Each of the methods is verifyable, however a heuristic method is the easiest to understand. Given these reasons, the greedy algorithm is selected as the method to use.

Literature suggests two ways to overcome the main weakness of a greedy algorithm. The first is to sort the tasks that need to be performed. Each task is assigned a performance cost, based on the cheapest crew member that can perform the task. That way, priority can be assigned to the tasks [72]. In case of the ship, this means assigning the tasks that have to be performed by the most expensive assignees first.

The second, and most powerful step, is to add additional constraints to the assignment problem. The mathematical background of the assignment problem sees each hour of one assignee as a single entity. However, once a (rank of) crew member has been selected to perform one task, it makes sense to also assign tasks to the other available hours of that assignee. That way, a crew is formed that has as full a workload as possible. This is done by adding in additional constraints that activate once a crew member is selected. This automatically lowers the total cost of the crew, as a crew member that works only a fraction of their possible workload is just as expensive as a crew member that has a full workload. A similar type of constraint is added that forces a task to be assigned to one crew member and not to multiple crew members. For example, once the captain has been selected to perform the task responsibility, it is the most economical if they are also assigned other tasks, to utilise their available hours. The detailed constraints that are added to improve the outcome of the greedy algorithm are given in Section 3.2.2.

3.2. THE CREW ANALYSIS ALGORITHM

This section explains the greedy algorithm that is set up to solve the problem of assigning all crew tasks to crew members that have the skill to perform them. The main aim of the Crew Analysis Algorithm (CAA) is to distribute the required tasks as efficiently as possible over the crew members. It does this by completing the algorithm for each task.

Before the algorithm is discussed, the input and output are investigated in more detail as these two elements are key in shaping the algorithm. Figure 3.2 shows the visual representation of the input and output data used.

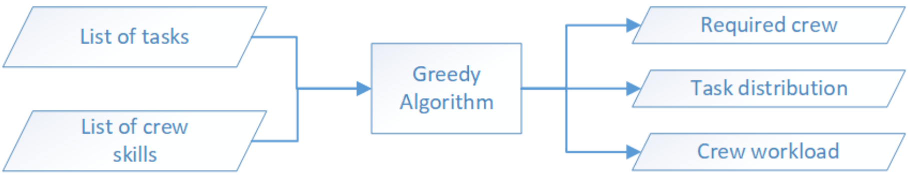


Figure 3.2: Input and output used for the crew assignment algorithm

3.2.1. INPUT

The input for the greedy algorithm consists of two databases and an overview of the cost for each crew member. These elements together are used to set up the cost matrix for the assignment problem. The first database is the overview of all the tasks that need to be completed, as discussed in Chapter 2. The second database is an overview of the skills that each different crew member has, based on their rank.

THE TASK DATABASE

For each task, several properties have been determined such as, among others, the hours required to finish the task, the number of crew members required and the travel phase in which the tasks takes place. Table 3.2 shows an example of the tasks database, showing which properties of the tasks have been investigated. The first attribute is denoted by *split possible*. Some tasks can easily be handed over to a replacement crewmember, while others cannot, which this column indicates. For example; in port access control is required to ensure that no unauthorised people come on board. This task can easily be performed by multiple people. However, a task like performing medical care is difficult to hand over to another crew member in the middle. Tasks that can be split are denoted by the value '1' and tasks that cannot be split are denoted by the value '0'. This column allows for the addition of additional constraints to the greedy algorithm, lowering the number of possible solutions. Having a task that cannot be split between multiple crew members means that one crew member must have enough hours available to perform the whole task. If that is not the case, the task will be assigned to another crew member.

The next column addresses the number of crew members that are required to perform the task. In many cases, multiple crew members are required to perform the same task. For example, maintenance sometimes needs to be performed by multiple crew members at the same time, and the mooring process requires multiple crew members to work together. To ensure that this task is not assigned to the same crew member multiple times, additional constraints are added here as well. The algorithm checks if the task has previously been assigned to a specific crew member and the crew member is removed from consideration if this is the case.

The next column is the number of hours that the task takes. A differentiation is made here between the two types of tasks. In case a task can be split over multiple crew members, the hours listed here are the total number of hours for multiple crew members. In case a task cannot be split, the hours listed here are per crew member. There are also tasks that do not cost any time but need to be assigned to a crew member regardless. An example of this is the task night watch in the engine room during normal sailing mentioned in Table 2.1. The engineer on duty is on call, but can sleep while performing this task. If there is a problem, an alarm will sound alerting the crew member.

The fifth column is titled 'simultaneous'. This is an additional constraint that is added to tasks that require crew members of different levels to work together. An example of this is the work planning, which takes place between a member from the bridge department, a member from the engineering department and the bosun from the deck department. To ensure that these crew members are available, and no other tasks are assigned first, the 'simultaneous' constraint is added. These tasks are assigned before other tasks. This prevents a situation where one of the required crew members has been assigned other tasks and a second crew member of that same rank is required only to perform this task.

The last three columns show in which of the three travel phases the task takes place.

3

Table 3.2: Example of the crew capabilities database

Task	Task properties				Relevant travel phase		
	Split possible	Number of crew involved	Total time in hours	Simultaneous	Loading and unloading	Arrival and departure	Normal sailing
Manoeuvring the ship during arrival and departure	0	1	1	0	0	1	0
Night watch in engine room during normal sailing	0	1	0	0	0	0	1
Watch in engine room during arrival and departure	0	1	1	0	0	1	0
Prepare deck for arrival and departure	0	4	1	0	0	1	0

This is required as the three travel phases are very different and the tasks in one travel phase have no direct relation to the tasks in another. Consequently, it is not one assignment problem that is completed, but three that are performed simultaneously. This is required because the crew members that are involved in one phase, are automatically also available in the other phases. The full database can be found in Appendix A.

THE CREW CAPABILITY DATABASE

On board of the *MV Endurance* there are ten different ranks of crew members possible. Each of these crew members has their capabilities with regards to the tasks that need to be performed. In this thesis, it is assumed that crew members either have the capability to perform a task or they do not. Table 3.3 shows an excerpt of the crew capabilities database, where '1' denotes that a crew member is capable of performing a task and '0' means that this is not the case.

The starting point for determining the capabilities of each of the crew members is their current set of tasks, as established during the field study described in Chapter 2. In addition to giving them these capabilities, each of the crew members has also been assigned the skills of their direct subordinates within the same department. For example, a captain can also perform the tasks of the chief officer and the second officer, even if they do not normally perform these tasks. On a ship, there is a very hierarchical manning system, meaning that crew members are promoted in a very linear career path. This allows for this assumption, as the captain will have been a second officer and a chief officer before becoming captain. It is assumed that crew members do not lose the skills they had previously. The full database can be found in Appendix B.

The crew capability databse provides a significant portion of the constraints for the CAA. The algorithm cannot assign tasks to crew members that do not have the required skill for the task, significantly limiting the number of possible choices that the algorithm can make.

Table 3.3: Example of the crew capabilities database

	Captain	Chief Engineer	First Officer	Second Engineer	Second Officer	Bosun	Cook	Able Bodied Seaman (ABS)	Ordinary Seaman (OS)	Deck Boy
Have responsibility for the ship	1	0	0	0	0	0	0	0	0	0
Have responsibility for the engine room	0	1	0	0	0	0	0	0	0	0
Port watch: Cargo supervision	1	0	1	0	1	0	0	0	0	0
Port watch: Access control	0	0	0	0	0	1	0	1	0	0

3.2.2. THE ALGORITHM

This section introduces the algorithm which has been designed, which is split into three main sections, the data preparation phase, and after that a division between tasks that can be split, and tasks that cannot be split. These three sections can be found in Figure 3.3 along with a more detailed visualisation of the steps that are taken in the task assignment. Additionally, the pseudo code of the algorithm is provided in Figure 3.4. The next step of the algorithm is the main element in which the tasks are assigned to different crew members.

CONSTRAINTS

Before the algorithm is explained, the constraints that govern the algorithm are explained. Important is that although the definition of the assignment problem uses 1 hour blocks of tasks and people, the further explanation of the algorithm speaks of crew members and tasks a whole blocks. The constraints for the algorithm are:

- Crew members can only be assigned tasks that they have the required skill for
- The assigned number of hours per crew member cannot exceed the available number of hours per travel phase
- Tasks that require multiple specific crew members (e.g., because only they have the required skill) are assigned first, from most expensive to cheapest
- The pother tasks are assigned most expensive to cheapest
- Some tasks have to be performed by one person and cannot be transfered one it is started

DETAILED OVERVIEW OF THE ALGORITHM

As mentioned in Section 3.2.1 the algorithm does not address one assignment problem but is a combination of three interdependent assignment problems, each addressing one of the travel phases. How this is done, is explained in Section 2.4. The three travel phases

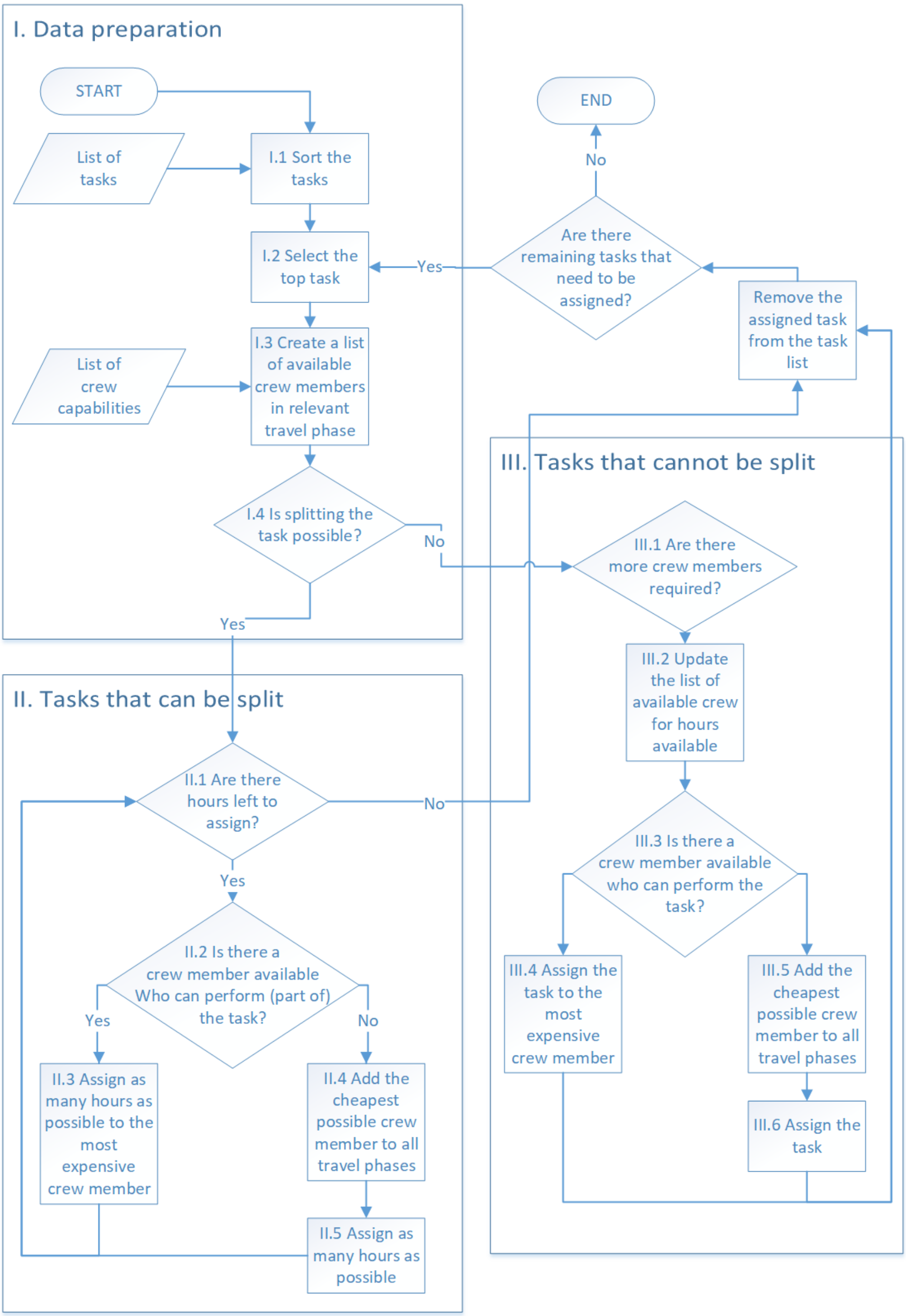


Figure 3.3: Details of the crew analysis algorithm

```
%% Starting operations for the algorithm
Create task database matrix [T] with elements t
Sort [T] on task cost most expensive to cheapest %Greedy algorithm improvement
Sort [T] Simultaneous – not simultaneous  % Keep cost sorting in place
Create crew skill database matrix [C]
Generate available crew members matrix [A] %empty at the start of the algorithm

%% Start the algorithm
Loop through [T] for all t
        Select the first element of [T] and extract task length h
        % Simultaneous tasks
        If simultaneous is true
                Determine crew with required skill from [A]
                Loop through the following steps for each crew member
                        If crew member is available
                                Assign t
                        Else create the required crew member
                                Assign t
                Update [A]
        %Non-simultaneous tasks
        Else if simultaneous is false
                If split is true
                        Loop through the following for 1 to h
                                Generate a list of crew members capable of performing the task
                                        If crew members in [A] are capable of performing the task
                                                Select the most expensive crew member
                                                Assign the as many hours as possible
                                        Else create cheapest crew member that can perform the task
                                                Assign as many hours as possible
                                                Update [A] for other travel phases
                                        Update [A]
                Else if split it false
                        Loop through the following to find a crew member to perform the whole task %(h hours)
                                Generate a list of all crew members capable of performing the task from [A]
                                        Eliminate all crew members with available time < h
                                        If a crew member remains to perform the task
                                                Select the most expensive crew member
                                                Assign the task
                                        Else create the cheapest crew member that can perform the task
                                                Assign the task
                                                Update [A] for other travel phases
                                        Update [A]
          Remove the assigned task t from [T]
```

Figure 3.4: Pseudo code of the algorithm

differ from each other in terms of tasks that need to be performed, but also in the regulations that govern them and the duration of the total travel phase. However, they are connected by the crew. Although the requirements might not be the same for each of the phases, the total crew will be, since the crew composition does not change during a voyage. Therefore, the tasks are all added to one database, to be divided afterwards. If a crew member is selected for one of the travel phases, they are immediately available for the other two phases as well.

When the algorithm is initialised (Section I in Figure 3.3), tasks are first sorted. The tasks are sorted based on two criteria, first whether or not they are simultaneous tasks, and second by their execution cost (i.e., the monthly cost of hiring the cheapest crew member that can perform the task).

Simultaneous tasks are tasks that require different levels of crew members, for example a work planning meeting. In the current conventional manning situation, this would require the chief officer, the chief engineer and the bosun as representatives from the three different departments on board of the ship. As long as there are crew members on board of the ship these meeting have to take place in some way. This means that in any given scenario a representative from each department with the required skill will be assigned this task. The separate assignment of the communal tasks takes place before the regular tasks are assigned. This is due to the fact that these crew members need to be on board to perform this task. As explained earlier, assigning the communal tasks first ensures that it is not possible that a crew member has been assigned a full work day (for example by receiving tasks that are below their pay grade) resulting in a second crew member of the same rank being required.

The first step (I.1) is to sort the tasks by their execution cost. This ensures that the crew composition that the program suggests is in fact the cheapest option (for a further explanation see Section II). This allows for the addition of extra constraints to reduce the possibility of the greedy algorithm resulting in a sub-optimal solution.

In the sorted task list, all tasks from all three travel phases are placed in the same list. When a task is selected (I.2), the available crew members for the relevant travel phase are determined and the task is assigned following either the steps in Section II or Section III. When a new crew member is required, this crew member is not only introduced in this travel phase, but also in the others. This means that for a task in a different travel phase this crew member can now be selected. The assignment of tasks and the number of hours assigned are completely separate between the travel phases. It is, for example, possible for a crew member to already have a full workload in one travel phase while having no tasks assigned yet in a second.

Starting with a crew of 0, the algorithm keeps track of all required crew members, their assigned tasks and how much time they have left in a workday to perform other tasks. This list, together with the requirements regarding the task, such as the required man hours to perform it, allows the program to set up a list with crew members on board who can perform the selected task (I.3).

The algorithm makes a distinction between how tasks that can be split between multiple crew members (Section II) and tasks that cannot be split (Section III) are assigned (I.4).

Tasks that can be split

In Section II of Figure 3.3, the tasks that can be split between crew members are assigned. This section concerns tasks that can easily be transferred to another crew member before completion, such as watch keeping. The algorithm executes a loop in order to assign all hours of the task to a crew member. There are two options to assign the hours: Either there is a crew member on board that can perform the task or there is not (II.2). If one or more crew members on board has the skills to perform the task, as many hours as possible are assigned to the most expensive available crew member (II.3). If there are no more tasks that require this crew member's specific skills, this crew member can now be assigned tasks that are below their paygrade. This ensures that the crew members have as full a workload as possible.

If there is no crew member on board that can perform the task, the algorithm creates the cheapest crew member capable of performing the task (II.4). Once again, due to the way the tasks are sorted in Section I, it is not possible that a more expensive crew member is required later on in the process. This means that the cheapest crew member possible is the most economical choice.

Tasks that cannot be split

In Section III of Figure 3.3 tasks are assigned that cannot be split among multiple members of the crew. An example of a task that cannot be split is the providing medical care. Once a crew member has started this task, the tasks cannot be transferred to another crew member. In general, the steps are very similar to the steps taken in Section II. However, in this case, the loop does not run until all hours are assigned but until the required number of crew members have this task assigned (II.3).

3.2.3. Output

Figure 3.2 shows that the greedy algorithm should provide three key results:

1. The composition of the crew (in total and per travel phase). This list of crew members can be used to quantify the effects of the replacement of tasks on the size and composition of the crew. This list can also be used to identify which travel phase requires the most crew members. This is the travel phase in which the workload needs to be reduced to lower the number of crew members on board.
2. The distribution of the tasks over these crew members. The distribution of tasks over the crew members gives key information about how the replacement of specific tasks might influence the composition of the crew before changes to the input are made. By looking at which tasks are performed by which crew member, an estimation of the effects can be made.

3. The total workload of each of these crew members. The workload of the crew members provides an insight in how well the tasks are distributed over the crew members. Ideally, each crew member works a full day, as that would be the most efficient use of resources.

3.3. CASE STUDY

To validate the model and to show how it works, a case study is performed. The ship studied during the field study, *MV Endurance*, is used because the current manning situation is known, making it easy to validate the results of the algorithm. This ship is used in the following chapters as well.

This section starts with an introduction of the reference ship. After that a model validation is performed by comparing the output of the model with the known manning situation of the *MV Endurance*. Finally, a case study is performed in which the navigation tasks are replaced and the new situation is investigated.

3.3.1. THE REFERENCE SHIP

The *MV Endurance* is a short sea container vessel that, at the time of the case study, sailed a liner service between Belfast, Northern Ireland and Antwerp, Belgium. The most important parameters of the ship are given in Figure 3.5.

Parameter	Size
Length over all	134,65 m
Crew	11
Capacity	750 TEU
Installed engine power	7200 kW
Deadweight tonnage	9450 ton
Gross Tonnage	7680 ton

Figure 3.5: The MV Endurance and some of the ship's key parameters

CREW COMPOSITION AND COST

Table 3.4 shows the crew members that are part of each of the aforementioned three departments, as well as their approximated cost for the operating company. The table also presents the number of each of crew ranks present on board of the reference ship.

3.3.2. MODEL VALIDATION AND VERIFICATION

Before the case study of replacing the navigation task cluster is performed, the model needs to be validated. As the model represents a real situation, this is done by investigating if the simulated situation matches the real situation. After that, tasks are removed systematically to investigate if the reassignment of tasks works as expected.

Table 3.4: Crew on board of the MV Endurance and approximate cost of these crew members for the operating company [crew cost obtained from JR Shipping]

Crew member	Cost for operation company per month [€]	Number of crew members on board of the *MV Endurance*
	Bridge department	
Captain	9,000	1
Chief officer	7,500	1
Second officer	4,200	1
	Engineering department	
Chief engineer	8,900	1
Second engineer	7,400	1
	Deck department	
Bosun	2,400	1
Cook	2,700	1
Able bodied seaman (ABS)	2,000	2
Ordinary seaman (OS)	1,800	1
Deck boy	1,400	1
TOTAL	**97,800**	**11**

It is known that the MV Endurance sails with 11 crew members, who all have a task during the normal sailing phase, each of which has a full workload. Figure 3.6 shows that there are indeed 11 crew members required during this travel phase. In the conventional situation, all crew members have a full workload every day. Additional repairs might come up, or standard maintenance is moved forwards. It is therefore difficult to give exact durations of some of the tasks. This explains why the second officer and the second engineer do not have a full workload in the modelled situation.

There is a difference between the crew presented in Table 3.4 and Figure 3.6 when looking at the crew members of the deck department. The reason for this difference is that in skill level, there is no difference between a deck boy and an ordinary seaman. This means that the algorithm will always select the deck boy over the ordinary seaman. However, in practice, there is a difference between the crew members in terms of experience. Due to the hierarchical nature of the crew organisation, there will always be crew members of different ranks to ensure promotions can be made and the hierarchy remains in place. However, adding constraints that ensure the hierarchical structure on board will severely hinder the possible crew combinations, especially when tasks are replaced in later stages. Additionally, the difference in cost between a deck boy and an ordinary seaman is small (i.e., €400 per month, and a €4,800 per year). On a total crew cost of €1,173,600 per year, this is not deemed significant.

However, the correct number of crew members is not the only thing that needs to be checked. Each crew member is assigned a correct number of hours, and not more. The number of crew members also matches the original number on board of the *MV Endurance*. However, it is still possible that the crew members are assigned tasks that they are not capable of performing. For that reason, a more detailed investigation into the assigned tasks is performed. This is done by checking a number of tasks that can only be performed by one crew member, and by looking into all the tasks assigned to one crew

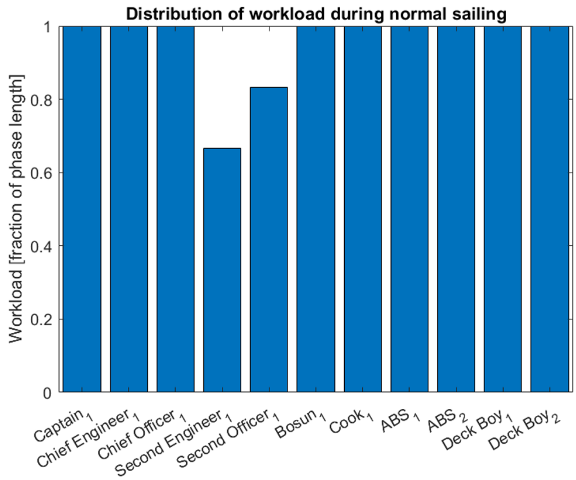


Figure 3.6: Crew requirements and task distribution during the normal sailing phase for the conventional ship

member. If this adds up, it can be concluded that the model represents the current situation well.

There are several tasks that can only be performed by one specific crew member. This includes, but is not limited to, the responsibility over the whole ship, the preparation of food and maintenance paperwork during both the loading and unloading phases. If the tool works correctly, these tasks will be assigned to the captain, the cook and the chief engineer respectively. A check of the results show that these tasks are indeed assigned to the intended crew members.

The final check consists of investigating if a single crew member only has tasks assigned that they can perform. If this is the case, it can be concluded that the model works as it should. Investigation of the assigned tasks shows that the tasks assigned to each of the crew members can indeed be performed by them. Additionally, the tasks the crew members have been assigned match with the tasks observed during the field study.

VERIFICATION OF TASK REMOVAL

With the previous checks, it has been shown that the task assignment algorithm gives a good representation of the current situation. Assuming that the current distribution of tasks is optimal, the algorithm provides an optimal answer for the current situation. However, before the algorithm is used for further analysis, it is also important to investigate if this also holds true when tasks are removed. In this section the following tasks are removed from all travel phases:

- Prepare food and drink
- Have responsibility for the engine room
- Work planning

- Do maintenance paperwork

With the removal of these tasks, both the cook and the chief engineer should have no tasks that only they can perform. The cook should be removed from the ship entirely. The remaining tasks that the chief engineer performs can also be performed by a second engineer. Therefore, the new required crew should have two second engineers, as there is no reason to select a chief engineer.

Figure 3.7 shows the new crew requirement that has been calculated using the CAA. As expected, the cook is no longer on board. Additionally, there are now two second engineers, instead of one chief engineer and a second engineer. Another difference from the workload in Figure 3.6 is the fact that now one ABS and three deck boys are required, instead of two ABS and two deck boys. This is due to the fact that the workload of the bosun has been reduced due to the removal of some of the tasks, which allowed them to take over some of the tasks of the ABS. This means that the second ABS is no longer required and a deck boy can take their place. As the algorithm returns the expected result, it can be concluded that the task removal works as expected.

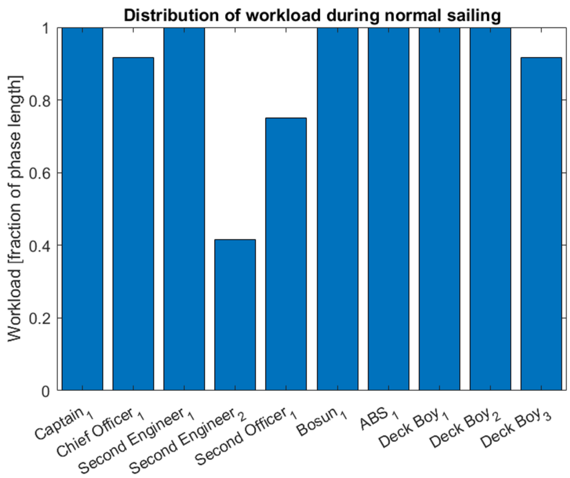


Figure 3.7: New crew requirement and workload after removing specific tasks

3.3.3. CASE STUDY: REMOVING THE NAVIGATION TASKS

To show how the algorithm works in practice, a case study is performed. In this case study, all the navigation tasks are removed. Automated and autonomous navigation is a well-researched topic, and is often seen as the key to unmanned sailing. This case study investigates whether this is a valid claim.

As mentioned above, the reference ship used in this research has a crew of 11. However, these 11 crew members are only required during the loading and unloading phase and the normal sailing phase. During the arrival and departure phase only 9 crew members are required (the chief officer and second engineer are not required). For this case study, the entire navigation task cluster (as presented in Table 2.1) is removed.

On a conventional ship the crew performs the following tasks with regards to navigation during the normal sailing phase: watch keeping on the bridge, and look-out duties at night. The watch keeping task consists of performing situational awareness, communication with other ships, keeping track of the ship's route and making changes to said route if required. For this case study it is assumed that all these tasks are taken over by a computer.

For the arrival and departure phase the following tasks have been identified to be part of the navigational tasks: Manoeuvre the ship, prepare bridge for arrival or departure and watch-keeping on the bridge. During the normal sailing period, the ship does not require active steering, most of this is done by the steering computer by waypoint following. This is different for the arrival or departure. In these cases, the captain manoeuvres the ship by hand. In this case study it is assumed that all of the abovementioned tasks are performed by a navigation system and that the crew does not need to perform these tasks anymore.

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tasks anymore.

NORMAL SAILING PHASE

The impact of the automation of the navigation tasks on the workload of the crew is significant during the normal sailing phase, especially for the bridge department. However, this reduction in workload does not result in any major reductions in the required number of crew members, as can be seen in Figure 3.8. The size of the crew decreases by only one crew member, the second officer. However, this figure also shows that for a number of crew members, the workload decreases significantly. For example, the chief officer (denoted by the third bar) goes from a full workload to one where he is only assigned tasks for less than 20% of the time. Such a low workload is an inefficient use of resources as it leaves several crew members with only a very low workload. Furthermore, it only leads to an absolute reduction of 1 crew member. If automating the navigation tasks is to have a more significant effect on the size of the crew of a ship, a radical change in task assignment is required, as will be explored in more detail in Section 3.3.4.

3

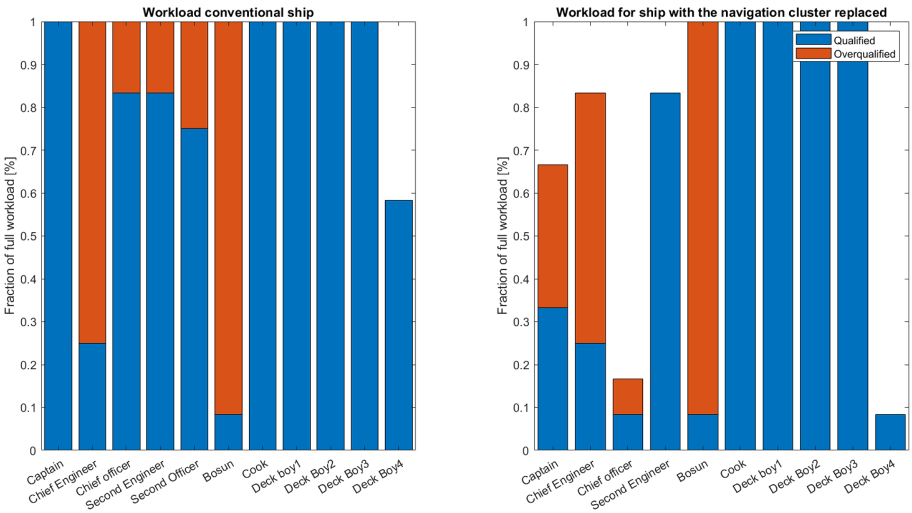

Figure 3.8: The required crew members and their workload for the conventional situation (left) and the automated situation (right)

ARRIVAL AND DEPARTURE PHASE

During the arrival and departure phase, the impact of automating the navigation tasks is relatively small. This is mostly because this phase normally does not take very long which means that only one crew member is required to perform the navigation tasks. In this case, the required number of crew members is reduced from 9 to 8, as the second officer is no longer required on board. The tasks that the second officer performs in the conventional situation have been transferred to other crew members on the ship that also have the ability to perform that task. For example; the second officer performs a supervision task during the arrival and departure phase, which is now performed by the captain.

Figure 3.9 shows that both the captain and the chief engineer perform only tasks for which they are overqualified during this phase, as becomes clear from the two light grey bars. The reason these two crew members are still selected by the algorithm is because they perform tasks called responsibility for the ship and responsibility for the engine room. The international regulations state that a captain must be responsible for the ship at all times and similarly a chief engineer must be responsible for the engine room [31]. While other crew members may have responsibility of either the ship or the engine room during their watch, the ultimate responsibility lies with the captain and the chief engineer. These tasks normally do not require any time to be spent on them but cannot be assigned to another crew member.

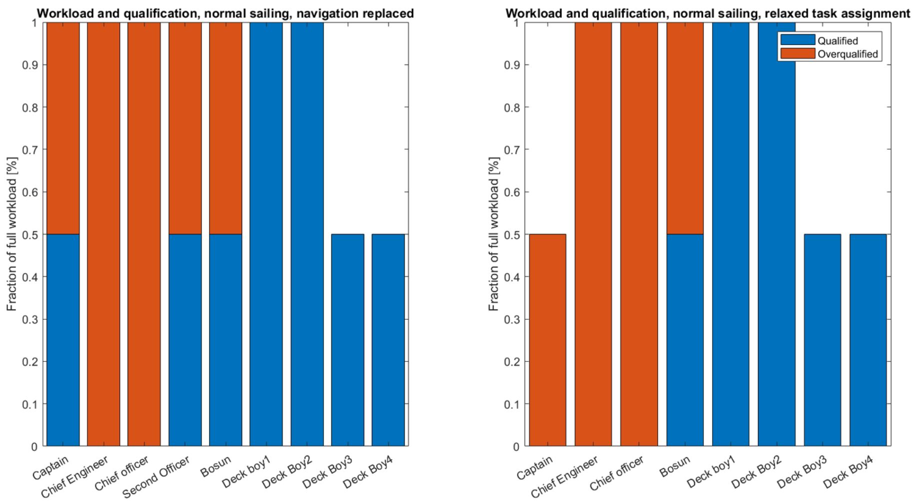

Figure 3.9: Workload and crew requirements for the arrival and departure phase in the conventional situation (left) and the automated situation (right)

3.3.4. Reconsidering the Traditional Task Distribution

In the previous section, tasks were shifted between crew members in the same department, which did not result in significant changes in the required number of crew members. However, the results did show a significant decrease in the workload of specific crew members, something that is not economically beneficial for the ship owner. In this study, the constraint that only allows crew members to perform tasks generally assigned to their own department is removed. This means that a crew member can now also perform tasks that are outside their department. However, a crew member must still have the required skill and skill level to perform a task.

Figure 3.10 shows that having crew members perform tasks from other departments allows for a further reduction of the crew size by two crew members, two deck boys, and a full workload for most of the crew involved. However, it also increases the amount of

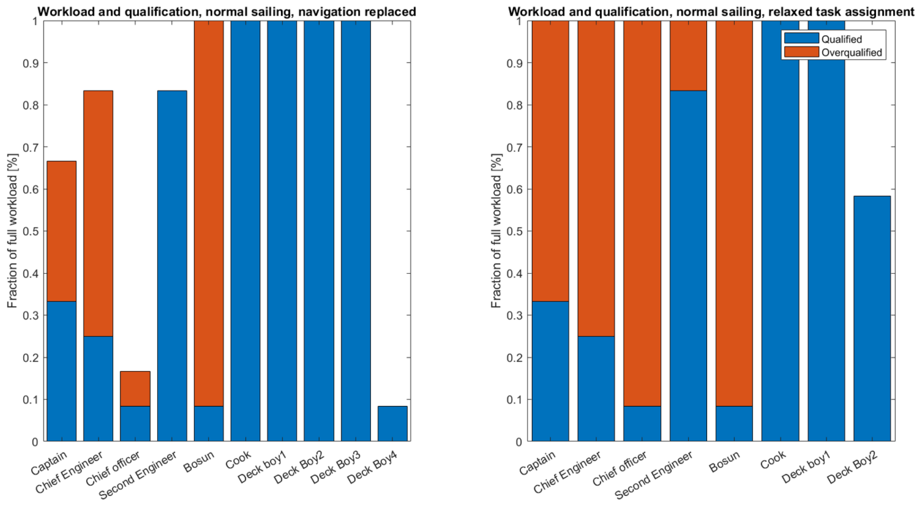

Figure 3.10: The difference in workload and crew composition during normal sailing between the automated situation with traditional task assignment (left) and without traditional task assignment.

time that crew members perform tasks for which they are overqualified, specifically the chief officer. This could negatively influence the work enjoyment of these crew members.

Table 3.5 gives an overview of the number of crew members that are required in the arrival and departure and the normal sailing phases. The table shows that not using the traditional task assignment causes a larger decrease in the required number of crew members in the normal sailing phase. The most important conclusion from this table is that in order to reach the full potential of automation, a thorough re-thinking of the way the ship and its crew operate is required. This means investigating changes in tasks for crew members, which in turn could mean a change in training. While this would require a radical change in the current culture, this case shows that it is crucial to achieve maximum benefit from automation of tasks.

Table 3.5: Summary of the required crew members per travel phase and situation

Travel phase	Conventional situation	Automated situation – Traditional roles	Automated situation – non-traditional roles
Normal sailing	11	10	8

3.4. CHAPTER SUMMARY

In this chapter the research question *how can the effect of replacing crew tasks on the composition of the crew be determined?*. There are many ways a problem like this can be approached. This research uses a greedy algorithm. To counteract the largest weakness of a greedy algorithm, the tasks are sorted from most expensive to cheapest and additional constraints are introduced based on the skill level of the crew members. Verification and validation of the results show that the algorithm works as expected, yields plausible results in known situations and can thus be used for further analysis. The case study presented at the end of this chapter shows how the algorithm works. It also allows for several preliminary conclusions.

1. If tasks are removed using the traditional task distribution, the removal of crew members is limited.
2. A more relaxed task distribution, in which crew members perform tasks from other departments, allows for a larger reduction in crew, as the workload is distributed more evenly across the remaining crew members.

The method will be used to determine the required crew for different combinations of clusters that are either replaced or not. To this end, Chapter 4 first investigates the solutions that exist to replace the different clusters of tasks. In Chapter 5, the method to generate the different combinations of clusters is discussed after which the CAA is used to analyse the crew requirements for all of the concepts. The new crew requirements are vital in investigating the economic viability of the selected concepts.

4

Exploration of potential solutions

In Chapter 3, the crew analysis algorithm was introduced. This algorithm is an essential part of the method to identify technically feasible and economically viable ship and manning concepts. To lower the crew requirement on board of ships, the previously identified task clusters must be replaced in some way. Therefore, an investigation into different replacement solutions is required. To determine the economic viability, a cost-benefit analysis needs to be performed. Before this analysis is performed in Chapter 5, this chapter investigates the costs of the proposed solutions. This chapter therefore addresses two of the research questions: *What technically feasible options are available to replace tasks on board and What are the costs associated with these technically feasible options.*

4.1. Approach

In Table 2.1 the tasks that the crew members perform have been combined into clusters. The proposed clusters have been validated by the same group of industry experts introduced in Chapter 2. With the help of these same industry experts, an assessment is made of the different solutions that can be used to replace the task clusters from the ship. There are three types of solutions:

1. a technical solution where a system is placed on board or on shore.
2. an organisational solution where the ship operator has shore-based personnel on the payroll to perform tasks that were originally performed by the crew, and, e.g. administration personnel or Shore Control Centre (SCC) personnel.
3. a solution where a service is hired from another company (i.e., hiring a maintenance crew or a shore crew). In these cases it is not profitable for the ship owner to

Parts of this chapter have been published in [38] have the personnel permanently available. In that case, it is assumed that services are offered by established companies, even if these services do not currently exist.

For each of the clusters, one or more likely solutions are presented. After that, a cost assessment is made of each solution.

4.1.1. COST ASSESSMENT

The estimations for the costs of the solutions are based on literature and existing systems. Some solutions are already commercially available. In that case, known costs are used. However, in many cases, solutions are not commercially available yet, making cost estimations more difficult. In that case, best estimates are used, using comparable solutions that are available (i.e., from other industries or similar but not exact solutions).

For each of the clusters, the additional costs are determined. The aim of this thesis is to judge the technical feasibility and economic viability of ship and manning concepts. The economic viability is determined by estimating if the concepts are significantly cheaper, significantly more expensive or approximately equally expensive as not replacing the affected task clusters. Although rough cost estimations are provided, it is not the intention to provide a highly detailed cost-benefit analysis, which is typically highly case-specific and requires detailed and highly reliable cost data. For that reason, several costs have been assigned a range in which they are expected to fall, leading to a best case and a worst case situation.

This chapter only addresses the direct additional costs that are incurred due to replacing a task cluster. There will be other changes, for example to the crew cost due to a lower crew requirement or a higher insurance, interest and maintenance cost due to additional systems being installed. These costs are addressed in Chapter 5, as part of the cost-benefit analysis.

ASSUMPTIONS REGARDING PERSONNEL

With regards to the personnel and their cost, two important assumptions are made. The first addresses the cost difference between on board crew and shore-based personnel. Depending on geographical location, on board crew members can be significantly cheaper than people working from shore. This is, for example, the case on the investigated route of the case ship, which operates between European ports. In the Netherlands, the minimum wage for jobs that require little specific training, is €1,635 per month [67]. Ghaderi [21](2019) states that the overhead cost on top of the salary of crew member is 36%. The total cost of employing a deck boy for a month is €1,400 (see Table 3.4). This means that the cost of employing a low skilled crew member on shore is 59% higher than that of an equally skilled crew member on board. For the crew cost, a lower and upper limit is used for the crew cost. The lower limit is the cost of the on board equivalent crew member. The upper limit is the calculated 59% above this cost. That way, a reasonable range for the crew cost is used.

The second assumption concerns the number of people required to perform a task. As shipping is a 24/7 business, many of the services offered are also 24/7. This means personnel needs to be available at all times. Kretschmann et al. [44] (2015) state that to cover a full time service, 5.7 FTE are required per position.

OPERATIONAL PROFILE OF THE REFERENCE SHIP

For a standard operating year, 360 sailing days are assumed [1]. Of these 360 days, 180 are spent in port and 180 are spent sailing, the remaining 5 days the ship is idle. This analysis is performed on a ship that sails for three days and then spends three days in port for loading and unloading. This means that the ship arrives in port 60 times per year.

4.2. ELABORATION OF THE TASK CLUSTERS

As mentioned above, 10 clusters have been established through a field study and discussions with industry experts. Below, each of the clusters and potential ways to replace them are discussed. Subsequently, the cost of the replacement is discussed.

4.2.1. CLUSTER 1: MOORING

The *mooring* task cluster requires a significant number of crew members to be safe for all involved. In this cluster the tasks that take place on deck are covered, but the manoeuvring of the ship during mooring is not. That task is covered under the navigation cluster. Mooring is a dangerous procedure and is therefore tightly supervised by high ranking personnel. It is performed in three pairs to increase the safety of the crew involved.

There are several existing automatic mooring systems [14, 50]. These systems are shore-based, which would require infrastructure adaptations in all ports that the ship visits. This complicates implementation and makes it more expensive. Alternatively, the ship could use an automated ship-based system that interfaces with the current infrastructure in ports (i.e., classic bollards). At this moment, no working prototype of such a system exists. However, one such solution has been suggested for use on the Yara Birkeland [48]. An alternative option for this is to take a shore crew on board to perform the mooring procedure.

Figure 4.1: Examples of automated mooring systems Left Cavotec's Moormaster [14] and right Macgregor's concept for the Yara Birkeland [47]

COST ASSESSMENT OF SHORE BASED MOORING SYSTEM

Several shore based mooring systems are in operation today. Díaz et al. [16] (2016) have performed a study on the feasibility of utilising such a system in the port of Santander, Spain. They determined a cost of €1,000 per port visit. With 60 port visits, the total cost would add up to €60,000 per year in usage cost.

COST ASSESSMENT OF MOORING CREW

Instead of using an automated mooring system, it is also possible to use a mooring crew. This crew would come aboard (for example with the pilot), perform the mooring operation and leave again. The length of a mooring operation differs between ships, port layouts, weather conditions and many other factors. Therefore, it is difficult to estimate how long a mooring operation will take. In this article, it is assumed that the whole mooring process, including sailing the crew to or from the ship, takes between one and three hours. Mooring of the ship requires 7 crew members at different levels of training: a second officer, 2 bosuns and 4 deck boys. The full calculation for the mooring cost is listed in Table 4.1.

It is possible for the mooring crew to travel to or from the ship with the pilot. This is an existing service. In the port of Rotterdam, the cost of this service is €500 for the whole crew [57]. From Table 4.1 it is concluded that the cost of using a mooring crew is significantly higher than using an automated mooring system. Therefore, only the automated mooring system is analysed further.

Table 4.1: Cost estimation for mooring crew

Factor	Value	Unit	Total per year
Port operations	120	Per year	
Usage of mooring crew	1 – 3	Hours per operation	120 – 360 hours
Crew cost	€114 - €181	Per hour	€13,600 – €65,200
Crew transport	€500	Per operation	€ 60,000
Overhead and profit (50% of crew cost)	€ 3,400 – 15,400	Per year	€3,400 – €15,400
TOTAL			**€ 77,000 – €140,600**

4.2.2. CLUSTER 2: NAVIGATION

The task cluster navigation covers the tasks that are performed on the bridge during normal sailing and the arrival and departure phase. The most common solution suggested for navigation is to design a system that can perform the navigation (and all tasks connected with this) autonomously. In all cases, there is a human as back-up, either on board or on a shore control station [44, 82].

However, a fully manned shore control station might not be required for a ship that is still manned. If some of the remaining crew members have navigation skills, they could bring the ship to safety should the autonomous system fail. This would significantly lower the requirements for the navigation system, both in terms of capabilities and in term of robustness, thus providing a workable solution until a more advanced system is available.

The requirements for the navigation system are most strict during the arrival and departure phase, when the ship is sailing in narrow, shallow and/or busy waters. Out in open sea, during the normal sailing phase, there is more space for manoeuvring, and less traffic. It is, therefore, likely that the navigation during the normal sailing phase is automated well before the navigation during the arrival and departure phase. However, there are currently no commercially available systems for either situation.

COST ASSESSMENT OF OPEN WATER NAVIGATION

Navigating in open water is easier than navigation near shore and in busy traffic lanes. Therefore, a relatively simple autonomous navigation system is required. Such a system is not yet commercially available and, therefore, there is no detailed cost information available. It is assumed that the autonomous navigation systems will work with the systems and sensors (e.g., radar, AIS) that are currently on board, which means that no further changes to the ship are required, as long as the ship is modern and is equipped with electronically controlled steering, radar, AIS and ECDIS. In the Horizon 2020 project NOVIMAR (www.novimar.eu/)(www.novimar.eu), a waterborne platooning concept is designed in which several ships automatically follow a leading vessel in close proximity. The project estimates that the smart navigation system in this concept costs €80,000 [25]. So, this value is assumed for lack of better data. This lifetime of this system is assumed to be 5 years.

COST ASSESSMENT OF AUTOMATING ALL NAVIGATION

When automating near shore navigation the navigation system must be able to also navigate in port, and place the ship next to the quay to be moored. This means that the navigation system needs to be more precise than a system that only operates in open water. For this research, the cost of the system is assumed to be double that of the open water navigation system, i.e., €160,000. The lifetime remains the same at 5 years.

In this step, when near shore navigation is implemented, bridge personnel will no longer be required on board. This means that the possibilities of the remaining crew to react to problems with the navigation system are limited. This implies that a shore control centre (SCC) is required, since nautical operations still need to be monitored. According to the MUNIN project, 1 operator is able to monitor 6 ships. In addition to this, a backup operator and a supervisor are required for every 5 (or less) operators [44]. This means that, ideally, a company operating a shore control centre would monitor a multiple of 30 ships, as it would be the best distribution of resources.

The office space of an operator is used 24/7 instead of only during normal business hours. Therefore, the costs incurred for the personnel to function (e.g., coffee, catering, office supplies), at a value of approximately €1,000 per year [28] are tripled. This means that the total annual cost for one 24/7 work station adds up to €11,800. Additionally, the work station of an operator is not the same as that of a regular employee. To monitor 6 ships, the MUNIN project [44] assumes a computer with significant processing power and 5 screens (one per ship) is required. They assumed that the cost of such a setup is

€2,600 per work station on top of the standard office cost. The lifetime of this equipment is estimated at 3 years by MUNIN.

According to the MUNIN project, a situation room is required per 15 ships [44]. This room is used in emergency situations. The cost of a situation room, which is capable of handling both engineering and navigation related emergencies is estimated to be €210,000. The lifetime of the situation rooms is estimated at 8 years, as they are used only occasionally, in emergency situations. For the propose of this research, the cost of a situation room only for navigation emergencies is assumed to be half of that, €105,000. As the SCC monitors 30 ships, two situation rooms are required. The total costs are summarised in Table 4.2.

Table 4.2: Cost estimation for near shore navigation

Factor	Value	Unit	Total cost per year for one ship
Cost of operators	€3,078,000 - €4,894,000	30 ships per year	€102,600 – €163,100
Cost of supervisors	€615,600 – €978,800	30 ships per year	€20,500 – €32,600
Cost of office space 24/7	€82,600	For all crew for 30 ships	€2,700
Investment cost navigation system	€160,000	5 years	
Investment cost hardware	€433	3 years	
Investment cost situation room	€7000	8 years	

4.2.3. CLUSTER 3: MAINTENANCE IN THE ENGINE ROOM

The engine room maintenance cluster contains both the planned and unplanned maintenance that is performed in the engine room. Currently, maintenance of vital engine components is a non-stop process that starts almost as soon as the engine is started. The engine room can be left unattended for several hours. However, discussions with seafarers have revealed that the number of malfunctions is still far too high to enable a ship to sail reliably without engineers. While there are several solutions to improve reliability of the main machinery, e.g., several generator sets instead of one main engine or two main engines [69] or a more steady state propulsion system such as a fuel cell or batteries (Kongsberg, n.d.; Tvete, n.d.), maintenance on these components is still required. This maintenance can be performed while the ship is in port.

When the ship is in port a maintenance crew will come aboard to perform all required maintenance. The maintenance crew needs to be aware of any repairs that need to be performed in addition to the standard scheduled maintenance. For this reason, the technical equipment needs monitoring while the ship is in transit. It also means that on shore, someone needs to analyse this data to determine which repairs are required.

4.2.3.1 COST ASSESSMENT FOR DIFFERENT POWER PLANT TYPES

In this thesis, fuel cells are selected for comparison to the conventional diesel engine. Additionally, a comparison is made with a situation in which the ship is equipped with multiple generators instead of one large engine. The investment cost of the different propulsion systems can be found in Table 4.3. Both the medium speed diesel engine and the generators are considered conventional propulsion, which means that there are sources regarding their investment cost. The investment cost for the PEMFC is not currently known, but consultation with an industry expert resulted in an estimation of 2,500 €/kW. In addition to the investment cost per kW, the table also gives the total investment cost for 7,200 kW, the power that is installed on board of the reference ship.

Table 4.3: Investment cost and service life of different propulsion types

	Medium speed diesel engine	PEMFC	Multiple generators
Investment cost	220 €/kW (Abma et al., 2018)	2,500 €/kW (industry expert)	350 [€/kW] (Interreg Danube Transnational Programme, 2019)
Investment cost for 7200 kW [€]	1,584,000	18,000,000	2,520,000
Service life	25 years	15 years	25 years

Regardless of the type of power plant that is selected, an engineer is also required in the shore control centre when the engineering crew is removed from the ship. This engineer can monitor the data coming in from several ships and determine the maintenance that needs to be performed. One engineer can monitor 30 ships at the same time [44]. The skill level of this engineer is set as chief engineer. This means that the yearly costs for one ship are €20,300 to €32,300 for the crew and €2,700 for the work space.

As mentioned above in Section 4.2.2, the SCC is equipped with situation rooms in case of emergencies. A situation room, for engineering problems, is now required. The additional investment for these more detailed situation rooms is €210,000, with a lifetime of 8 years. Per ship, this is an additional investment of €7,000, over 8 years.

In addition to the SCC personnel, an on shore maintenance crew is also required. It is assumed that a maintenance crew is hired for all days that the ship is in port, so 180 out of 365 days. In the MUNIN project, the size of the on shore maintenance crew is derived from the on board engineering crew [44]. This approach is also taken in this research. On board of the reference ship, the engineering crew consist of a chief engineer and a second engineer. However, in some cases crew members from the deck department come in and assist. For that reason, an on shore crew of 4 crew members is assumed, a chief engineer, a second engineer and two deck boys. The total cost of the maintenance crew ranges between €114,600 and €182,200.

4.2.4. CLUSTER 4: MAINTENANCE ON DECK

The maintenance on deck consists of: cleaning and maintenance of the superstructure and the hull, maintenance of the hatch covers and the safety equipment, and any repairs required on this equipment. Normally, these tasks are performed during sailing; however, these works do not need to be done continuously. A similar solution as for the engine room maintenance can be set up for this type of maintenance. In port, a maintenance team can go aboard to clean the ship and to repair whatever is necessary.

Much of the maintenance on deck is general upkeep of the ship, such as cleaning and painting. While a significant portion of the workload of the deck crew consists of these tasks, it is difficult to quantify how much of the work is strictly required and how much is done because the crew is available anyway. For the purpose of this study, the following replacement solution is proposed, based on interviews with industry experts (i.e., teachers from different Dutch nautical schools, each with extensive sailing experience):

- Every month a team is sent on board to clean the walkways and other internal spaces to keep them accessible and safe.
- The hull maintenance (i.e., cleaning and painting) is performed during survey and docking periods.

The cleaning crew will consist of two people that are hired for 8 hours each, while the ship is in port. The skill level of these people is assumed to be equivalent to that of a deck boy. In the five days that the ship is not in service, the maintenance of the hull and superstructure needs to be performed. This includes chipping, painting and other general maintenance. As this task is normally performed while the ship is at sea, it is difficult to predict the amount of maintenance and the time it will take to complete it. In this dissertation, it is assumed that the maintenance is performed by one team, consisting of a bosun and between 10 and 20 deck boys. Table 4.4 shows the calculation of the total cost for this cluster.

Table 4.4: Cost estimation for maintenance on deck

Cost factor	Value	Unit	Total cost per year
Cleaning – deck boy	€100 - €160	Per day	€6,000 – €9,600
Maintenance - Bosun	€450 - €715	Per day	€2,300 - €3,600
Number of deck boys	10 – 20	Per day	
Maintenance - Deck boy per day	€100 - €160	Per day	€5000 – €16,000
TOTAL			€13,300 – €29,200

4.2.5. CLUSTERS 5: BUNKERING, 6: ADMINISTRATION AND 7: PORT SUPERVISION

Clusters 5, 6 and 7 have little in common with each other but can be solved using a similar solution. The bunkering process is performed mostly by staff of the bunkering company, while a crew member assists them with the bunkering and ensures that the fuel is loaded correctly. Both during loading and unloading and during the normal sailing phase of the ship, several important administration tasks need to be performed. The loading plan for the new journey needs to be checked, bills of lading need to be signed, customs needs to be cleared and some crew administration, needs to be performed. Currently, many of these tasks are performed by either the captain or the chief officer.

Finally, there is a task cluster port supervision. This cluster encompasses the support to people coming onto the ship. This could for example be an external engineer assisting with repairs on the ship. Additionally, this task cluster entails ensuring that the ship is safe in port, supervising the loading process and ensuring that the mooring lines stay secure and tight.

The most logical solution for all of these clusters is not a technical one. While many of the individual aspects of these tasks could be automated, it is highly likely that a person performing these tasks will be cheaper and equally effective.

Additionally, from expert interviews it was found that ship owners want to have control over who enters their ship. For most of the activities mentioned above, external personnel need access the ship. It would be an unprecedented leap of faith for commercial shipping to relinquish this control by the operator. At this point, it seems unlikely that this will be the case. Therefore, an agent to represent the ship and its operator is deemed a logical solution. Since it is already common to have an agent in destination ports, this is not considered a major challenge.

COST OF BUNKERING

Should this task be replaced separately, a crew member with the skill of a second engineer would be required. Monitoring the bunkering process can take anywhere from 1 to 4 hours. According to industry experts, how often a ship bunkers depends on factors such as its cargo, the location where the ship sails, the distance a ship sails and the availability and cost of the fuel, to name but a few factors. Based on a discussion with an industry expert with over 20 years of sailing on large cargo ships and teaching the next generation of sailors, it is assumed that the ship bunkers after two complete trips. This means that bunkering takes place 30 times over one year. This results in a crew cost ranging between €1,700 and €11,000. However, it might also be possible for this task to be performed by the personnel hired to cover the task port supervision, which is discussed below.

COST OF ADMINISTRATION

Based on expert interviews, it is assumed that in case of full automation, 2 hours of administration work is required daily for one ship. The administration mostly pertains to the cargo, customs and insurance. All this work can be performed from an office. The person that works on the administration, requires a skill level of a second officer. This means that one administrator can cover 4 ships, splitting the cost between them. The yearly personnel cost ranges from €12,600 to €20,000 per ship. The yearly cost of one office space, including office supplies, furniture etc. is approximately €9,800 [28]. This means a cost of €2,500 per ship per year.

COST OF PORT SUPERVISION

Access control and monitoring of the ship can be solved relatively easily and cheaply with electronic access gates and cameras, costing an estimated €2.500 [35] for the access gate and €20.000 for the security system [**RichmondAlarm** , 13]. For these systems, a lifetime of 5 years is assumed.

Monitoring of the loading and unloading process as well as the access control can be done by the ship's agent. This agent will represent the ship as long as it is in port. For a fully unmanned ship, this means letting external personnel on board, representing the ship with port authorities and customs, providing the required documents and ensuring that the loading plan is followed. Due to the relatively high level of responsibility of this task, it is assumed that the agent's pay is equivalent to that of a chief officer. The ship is in port for 180 days out of the year. This results in a total personnel cost of €253,000 - €402,300 per year.

4.2.6. Cluster 8: Responsibility

While on the ship, the captain has final responsibility for the ship. This means that they make the final decisions and can ultimately be held responsible for things that go wrong. On an unmanned autonomous ship, there is no ultimate responsibility on board. This is currently not allowed by law [31] (International Maritime Organization, 2000) but, if a person on shore can be provided with sufficient situational awareness and capability to intervene, there is no fundamental reason why this responsibility cannot be taken on shore. The same goes for the responsibility of the chief engineer in the engine room. The IMO has been working on adapting their regulations towards low and unmanned ships [30] and it is assumed that allowances for this will be made in due time.

The cluster responsibility only needs to be transferred to the shore control station when there is no crew left on board. As the shore control station is by then established, there is no additional cost for replacing this cluster.

4.2.7. Cluster 9: Cargo conditioning

The movement and vibrations of the ship can cause problems, such as loosening the lashings of containers. To prevent stacks of containers from falling over, the lashings need to be refastened during the voyage. This is done by the deck crew, who check them at least once per day. By equipping a container ship with above-deck cell guides, as opposed connecting the containers with twistlocks and lashings, the containers will remain stable on the ship.

According to industry experts, the loading and unloading speed of a ship equipped with cell guides is similar to that of a standard ship. Additionally, the steel weight of the cell guides, is offset by the fact that the ship no longer requires hatch covers [6]. Using the steel weight as the indicator for the cost of this solution means that using cell guides does not change the investment cost of the ship.

4.2.8. Cluster 10: Crew support

This cluster encompasses two tasks that are vital for the survival of persons on the ship; preparation of food and provision of medical care. Automating medical care is not possible. While there are possibilities for automation within the food production industry, these options to not seem feasible on board of a ship. As long as there are humans on board of the ship, both these tasks need to be performed. However, it is to be expected that at some point, the ship will, no longer have a dedicated cook. The medical care will be required as long as there are crew members on board. This means that a crew member always requires some medical training. Crew members all have basic medical training as part of their skill set. The cost of additional medical training is assumed to be negligible. The same goes for process changes that stem from crew members having to prepare their own meals.

4.2.9. COST SAVINGS FOR UNMANNED SHIPS

When the ship is fully unmanned the accommodation and several crew supporting systems can be removed from the ship. The removal of these systems will decrease the building cost of the ship. Frijters [20] estimates that the cost savings for a container feeder are 15%. For the ship in this analysis, a saving of 15% adds up to €2,300,000. The lifetime of these changes is assumed to be 25 years (i.e., the same as the ship itself).

4.3. CHAPTER SUMMARY

This chapter answered the research questions *What technically feasible options are available to replace crew tasks on board?* and *What are the costs associated with these technically feasible options?*. In Table 4.5, the solutions mentioned in this section are summarised. One of the elements that is used in Chapter 5 to determine which cluster to replace is the implementation time. Therefore, an indicative time frame is given in which it is expected that this solution will be available. This timeframe is an indication and is based either on the TRL of the technical solution, or the number and type of changes suggested for an organisational solution.

Table 4.6 shows the additional costs that are required to replace each of the task clusters. The costs have been split into additional investment costs, shore crew cost and usage cost. These costs will help to determine the economic viability of different manning concepts. Before the economic viability of any manning concept can be determined, these concepts need to be created. After that, a cost-benefit analysis is performed. Both these elements are discussed in Chapter 5.

Table 4.5: Summary of the presented solutions and their expected implementation time

Cluster	Potential solutions	Timeframe
Mooring	a) Automated mooring system that interfaces with the current quayside infrastructure. b) Shore crew that comes aboard the ship to perform mooring tasks	Available now
Navigation	a) Computer aided navigation per ship during normal sailing phase. b) Shore control station that monitors several ships at the same time	a) 5 – 10 years b) 10+ years
Maintenance in engine room	Maintenance is exclusively performed by maintenance team while the ship is in port.	Available now - 10 + years, depending on the selected propulsion method
Maintenance on deck	Maintenance is exclusively performed by maintenance team that performs their tasks while the ship is in port.	Available now
Bunkering	Supervision of bunkering is performed by an agent of the ship owner	Up to 1 year, organizational change
Administration	Administration is performed at the office of the ship owner	Up to 1 year, organizational change
Port supervision	Tasks are performed by an agent of the ship owner	Up to 1 year, organizational change
Responsibility	Cannot be automated under the current regulations, ideally the responsibility would be transferred to the shore control station	10+ years. This cluster can only be replaced if regulations allow it and a shore control station is available.
Cargo conditioning	Cell guides	Available now
Crew support	Tasks cannot be performed off the ship and will need to be performed in some way while the ship is manned	Only when no people remain on board

Table 4.6: Summary of the required crew members per travel phase and situation

Cluster	Additional investment cost [€]	Yearly shore crew cost [€]	Yearly usage cost [€]
Mooring – shore based system	-	-	60,000
Open water navigation	80,000	-	-
Near shore navigation	167,400	123,100 – 195,700	2,700
Maintenance in the engine room – PEMFC	18,000,000	134,900 – 214,500	2,700
Maintenance in the engine room – generators	2,520,000	134,900 – 214,500	2,700
Maintenance on deck	-	13,300 – 29,200	-
Bunkering	-	1,700 – 11,000	-
Administration	-	12,600 – 20,000	2,500
Port supervision	22,500	253,000 – 402,300	-
Responsibility	-	-	-
Cargo conditioning	-	-	-
Crew support	-	-	-
Design changes	-	-	-2,300,000

5

FINDING ECONOMICALLY VIABLE CONCEPTS

IN the previous chapter solutions to 10 task clusters were introduced. In this chapter, these clusters are used to generate possible ship and manning concepts, out of which a number of logical concepts are selected. That way, *the research question: What ship and manning concepts are likely candidates for the development path towards unmanned ships* can be answered. While much of the research aims to develop unmanned ships, there are likely to be intermediate steps as the technology required for sailing fully unmanned matures.

In Chapter 4 a distinction was made between automating the navigation in open water and automating navigation near shore. For that reason, the cluster navigation is split into two clusters; open water navigation and near shore navigation. With 11 clusters, there are $2^{11} = 2048$ different combinations of remaining and replaced clusters possible. These combinations are the ship concepts referred to in this thesis. As a result, assessing various options is not straightforward and the approach should be selected with care.

This chapter begins with an investigation of methods to develop the ship concepts. After a method is selected, this method is executed to find the logical concepts. A cost-benefit analysis is then performed on the selected concepts to investigate their economic viability. This is visualised in Figure 5.1.

5.1. METHODS TO GENERATE CONCEPTS

To set up different ship and manning concepts, methods to set up scenarios are used as a basis. Scenarios deal with a large set of options and uncertainty in the future. The methods allow for a structured way to analyse a large number of possibilities. Both of these

Parts of this chapter have been published in [38] and [37]

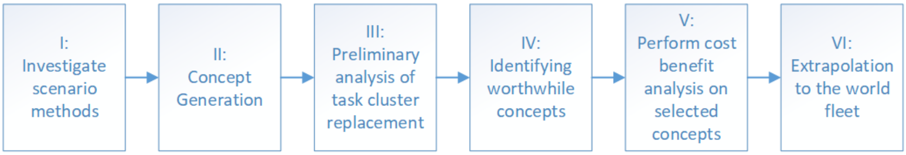

Figure 5.1: Overview of steps taken in this chapter

characteristics are also useful in analysing the different ship and manning concepts.

There are three distinct methods to set up scenarios: deductive, inductive and normative [77]. In the deductive method, two critical uncertainties are identified. These two uncertainties can be anything that can have a significant effect on the scenario but that is currently unknown. Examples of these uncertainties are; demand for a product, the price of a key resource, or the exchange value between two currencies. The next step is to identify the extremes that belong to these uncertainties. These four extremes are put on a two-axis system which results in a four quadrant matrix, in which each of the four quadrants represents a concept (see Figure 5.2 Using these four quadrants allows the users to imagine aspects that they would otherwise not have imagined [60]. As a result, the method provides four scenarios that are as different from each other as possible while staying within reasonable options [23]. A strategy can be set up for each of the four quadrants. The deductive method is most suited for cases where it is possible to define two dominant factors that are both highly uncertain [23, 77].

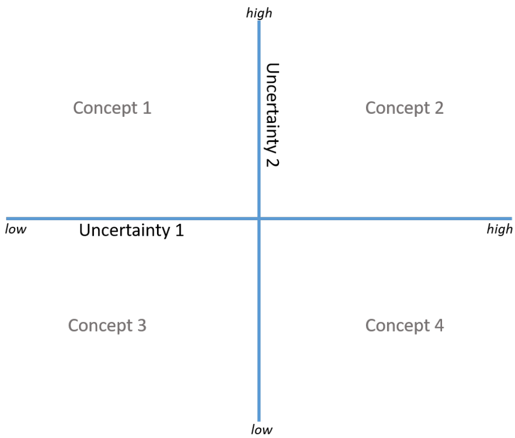

Figure 5.2: Graphical representation of the deductive method

For inductive scenario building, a chain of events is set up that creates plausible for the future. These chains are built around a *What if* question. From there, question such as;*what would cause this event* and *what would be the consequences of this* can be investigated [60]. Figure 5.3 gives a graphical representation of the method. Together, this creates a chain of events that form a scenario [77]. This method can lead to good results but is very unstructured and requires significant creativity and imagination to get the desired results [60]. This also means that the results are subjective, which can lead to a lot of debate regarding the validity of the findings.

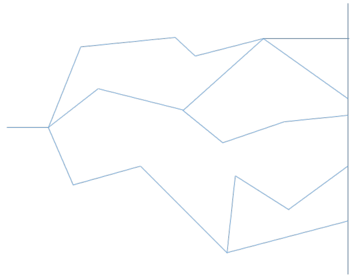

Figure 5.3: Graphical representation of the inductive scenario method

The normative method is similar to the inductive method. This method works with an *Official future*, a final scenario somewhere in the future (see Figure 5.4. The different paths towards this goal are investigated. Although this method also uses the *What if* questions, this method is more systematic than the inductive method described above as the user knows the end goal [60]. This means that the results are also less subjective.

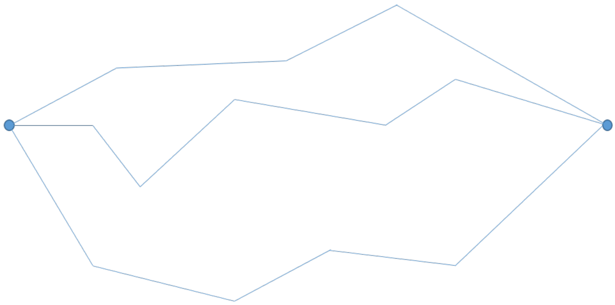

Figure 5.4: Graphical representation of the normative method

5.1.1. METHOD SELECTION

The goal of setting up the different ship and manning concepts is to find logical intermediate steps between the conventional situation and unmanned ships, which can be taken as 'the official future'. As both the starting point and the final situation are very clear, the normative method is automatically the favourable method.

The deductive method is very well suited for setting up company strategies based on a small number of uncertainties that can be defined in two extremes. This is not applicable to the problem of this thesis, as replacing a cluster gives only 2 options (yes and no). This makes it impossible to define the uncertainties in two extremes. The inductive method is an option as for each cluster the question what happens to the required crew and the design of the ship if this cluster is replaced can be asked. However, as the goal is known, using the normative method is preferred over using the inductive method.

5.2. CONCEPT GENERATION

The first step in identifying logical concepts is to set up all possible concepts and the corresponding required crew composition. This is done using the crew analysis algorithm (CAA) introduced in Chapter 3. The CAA is run repeatedly for each of the 2048 different concepts, as shown in Figure 5.5. The concepts consist of a cluster either being replaced or not being replaced. The binary characteristic of the concepts is used to systematically generate them. Each concept is numbered from 0 to 1023, in the figure denoted by n. This number is converted into a binary number, with zeros being added to create a 10 digit number. For example, concept number 117 becomes binary concept number 0001110101. The clusters that are denoted by a 1 are replaced and the clusters denoted by 0 are not. This is also represented in Table 5.1. This information is used to update the task list for the new concept after which the CAA is run for the concept. The output is stored in a database. After completing the run, n is increased by 1 until all concepts have been calculated by the CAA. By calculating the required crew composition in all scenarios, it is possible to get a complete overview of the effects of the removal of all combinations of task clusters. The results are presented in a heat map.

Table 5.1: Explanation of the binary definition of the concepts

	Mooring	Navigation	Maintenance in the engine room	Maintenance on deck	Bunkering	Administration	Port supervision	Cargo conditioning	Responsibility	Crew support
Concept 117	0	0	0	1	1	1	0	1	0	1
Replaced?	No	No	No	Yes	Yes	Yes	No	Yes	No	Yes

5.2.1. PRELIMINARY ANALYSIS OF TASK CLUSTER REPLACEMENT

In this section, a preliminary analysis of the generated concepts is performed. First, the difference between the traditional task assignment and the more relaxed task assignment, as identified in Chapter 3, is investigated for all concepts. After that, an assessment is made of the cost-savings of each of the concepts.

Figure 5.6 shows a heat map for the required crew with traditional task assignment (as discussed in Section 3.3.4). The horizontal axis shows the crew that is required for a given concept, while the vertical axis shows the number of clusters that are replaced. On the top right, the base scenario can be found, zero clusters automated and 11 crew

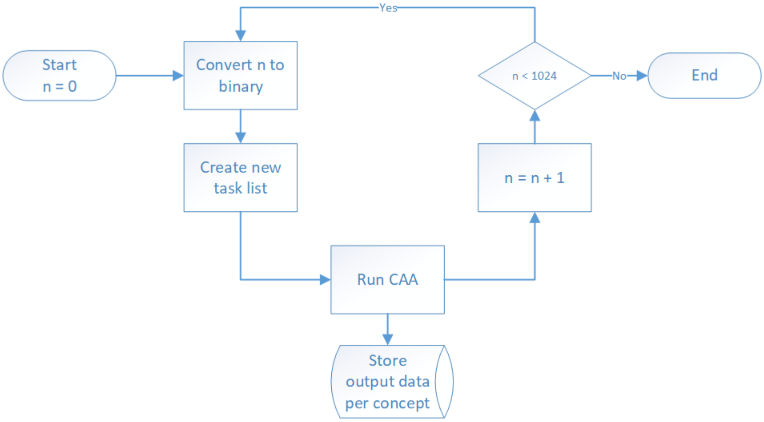

Figure 5.5: Overview of concept generation combined with CAA

5

members required. The final case, zero crew members remaining and 10 clusters automated, is on the bottom left. The numbers in between show how many concepts that exist that have the same number of clusters automated and require the same number of crew members. For example, the column titles '8' shows all concepts that require 8 crew members, 314 in total. This number of crew members can be achieved by replacing between 3 and 9 clusters.

The columns in between illustrate how many scenarios there are that require a specific number of crew members at a specific number of replaced clusters. In this figure, the maximum crew required for the trip (i.e., the crew required in the critical phase) is taken as the input. In some cases, this is in the normal sailing phase, while in others it is in the arrival and departure or the loading and unloading phase.

Traditional task assignment	Required crew: 0	1	2	3	4	5	6	7	8	9	10	11
Automated clusters: 0	0	0	0	0	0	0	0	0	0	0	0	1
1	0	0	0	0	0	0	0	0	0	0	6	4
2	0	0	0	0	0	0	0	0	0	11	28	6
3	0	0	0	0	0	0	0	0	8	59	49	4
4	0	0	0	0	0	0	0	8	52	109	40	1
5	0	0	0	0	0	0	12	37	99	89	15	0
6	0	0	0	0	1	8	35	55	75	34	2	0
7	0	0	0	1	7	25	26	30	26	5	0	0
8	0	0	2	5	9	13	6	6	4	0	0	0
9	0	0	5	1	3	0	0	1	0	0	0	0
10	1	0	0	0	0	0	0	0	0	0	0	0
	1	0	7	7	20	46	79	137	264	307	140	16

Figure 5.6: Heat map of the different concepts in the traditional task assignment

The case study performed in Section 3.3.3 has shown that having the traditional task assignment inhibits the removal of crew members from the ship as it leads to a relatively large crew, often with a low workload for several crew members. However, this case study was only performed for a specific case. By analysing all the clusters, a more general conclusion can be drawn regarding the relaxation of the task distribution. Figure 5.7 shows the heat map of the relaxed task assignment.

Relaxed task assignment	Required crew											
Automated clusters	0	1	2	3	4	5	6	7	8	9	10	11
0	0	0	0	0	0	0	0	0	0	0	0	1
1	0	0	0	0	0	0	0	0	0	4	2	4
2	0	0	0	0	0	0	0	0	5	26	8	6
3	0	0	0	0	0	0	0	3	40	61	12	4
4	0	0	0	0	0	0	4	27	103	67	8	1
5	0	0	0	0	0	5	24	68	116	37	2	0
6	0	0	0	0	4	22	40	71	63	10	0	0
7	0	0	0	2	13	31	22	34	17	1	0	0
8	0	0	3	5	13	10	4	8	2	0	0	0
9	0	0	5	1	3	0	0	1	0	0	0	0
10	1	0	0	0	0	0	0	0	0	0	0	0
	1	0	8	8	33	68	94	212	346	206	32	16

Figure 5.7: Heat map of the different concepts in the traditional task assignment

In the base scenario, there is no difference between the requirements for the traditional or the relaxed task assignment. In general, however, the concepts require a smaller number of crew members. Figure 5.8 shows the difference in crew requirement between the traditional and relaxed task assignment. It shows that the relaxed assignment is consistently more to the left, indicating that, on average, fewer crew members are required for each scenario and that there are more options to achieve any given crew reduction.

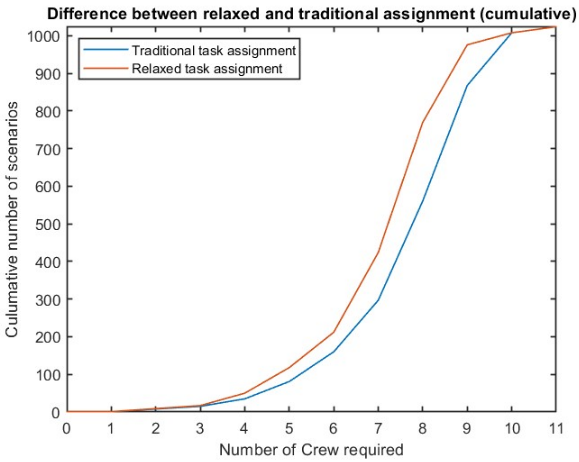

Figure 5.8: Heat map of the different concepts in the traditional task assignment

Instinctively, the topmost solution of each column of Figure 5.7 (as much crew reduced by replacing the smallest possible number of tasks) may seem like the best situation. However, this conclusion cannot be drawn yet, as the cost of the replacement solution is not taken into account and it is not specified which crew members are removed (e.g., removing the captain saves more money than removing two deck boys). Therefore, further analysis is required to investigate which of the concepts need to be replaced in which order.

CREW COST

From the algorithm, it is also possible to determine the crew cost for each of the scenarios. In the base case, the cost for the total crew is €1,207,200 per year. For the scenarios to be economically feasible, the cost savings from a smaller crew must be equal to or larger than the investment and operating cost of the replacement solutions. Figure 5.9 shows the crew cost as a function of the number of clusters that are replaced. The top row of the figure shows that there is a significant number of scenarios (i.e., 272) that reduce the crew cost by a maximum of just over €10,000 per month, or €120,000 per year, even if up to 6 clusters are replaced. This does not provide a significant budget to implement alternative solutions for the task clusters that are to be replaced. The figure also shows that each of the 32 options in which only one cluster is automated falls within this category (in the top right corner). It is therefore very likely that only automating one cluster does not allow for enough reduction in crew cost to be justifiable.

All phases (Monthly crew cost in euro)	Clusters removed: 10	9	8	7	6	5	4	3	2	1	0	
> 90001	0	0	0	0	1	8	28	44	32	10	1	124
80001 - 90000	0	0	0	5	35	97	112	60	12	0	0	321
70001 - 80000	0	0	4	29	84	102	62	16	1	0	0	298
60001 - 70000	0	0	4	24	49	37	8	0	0	0	0	122
50001 - 60000	0	1	11	40	36	7	0	0	0	0	0	95
40001 - 50000	0	1	11	13	3	1	0	0	0	0	0	29
30001 - 40000	0	2	9	8	2	0	0	0	0	0	0	21
20001 - 30000	0	4	6	1	0	0	0	0	0	0	0	11
10001 - 20000	0	1	0	0	0	0	0	0	0	0	0	1
0 - 10000	1	1	0	0	0	0	0	0	0	0	0	2

Figure 5.9: Heat map of the different concepts in the traditional task assignment

Again, there are many different ways that a specific cost range can be reached. In line with the findings above, very few conclusions regarding which scenario is best can be drawn from Figure 5.9, apart from the fact that automating a single task cluster will not lead to major cost savings and that further investigation is required to find the best way forwards. For such insight, it is necessary to analyse the effect of replacing individual task clusters in more detail.

PRELIMINARY CONCLUSIONS

To summarise, the following conclusion can be drawn from the preliminary analysis above:

- In general, the relaxed task assignment results in smaller crews when clusters are replaced. Therefore, the relaxed task assignment should be implemented as soon as any cluster of tasks is replaced.
- There are many concepts that are likely to lead to limited savings as they have a limited effect on the crew size

5.3. IDENTIFYING WORTHWILE CONCEPTS

Section 5.2.1 showed that randomly selecting concepts in the hope that they will cause a reduction in crew and crew cost is not likely to lead to good results. Therefore, a preliminary analysis is required to determine if a scenario is worthwhile. A logical path is identified through the scenarios using the normative method previously explained above. The results of the CAA (i.e., the required crew composition) can be used to answer questions regarding the concepts. However, only selecting a concept based on the crew reduction is not possible, as there are too many options that wield the same results. Therefore, a set of selection steps is set up to reduce the number of possibilities.

The steps that are taken are as follows:

1. The clusters that are removed all take place in the critical phase of the voyage (i.e., the phase that requires the most crew members). Removing crew members from another phase will not lead to a reduction of the required crew.
2. The economic impact of the clusters is investigated. Scenarios will only be considered if it is likely that there is potential for an economic benefit for the ship owner. This is not a full economic analysis but based on the estimated implementation cost of the clusters as determined in Chapter 4.
3. Of the remaining clusters, the replacement options with the highest TRL or the shortest time to maturity time are selected.
4. The cluster with the highest impact on the size of the crew is selected.

The cluster that emerges is replaced and the process is repeated. The information provided in Table 4.6 and Table 5.2 is used. Table 4.6 provides information on the economic impact and the expected TRL. Table 5.2 gives information regarding the number of crew members that are involved with each task cluster during each of the travel phases. This is key information determining the cluster that has the highest impact with regards to the size of the crew. Following these steps leads to the results presented in Table 5.3.

5.3.1. CONCEPT 1

The required crew in the conventional situation, as described on the top row of Table 20, is: 11 crew members in the normal sailing phase, and 9 for the arrival and departure phase and the loading and unloading phase. This means that the first replacement of a task cluster will need to take place in the normal sailing phase. The normal sailing phase encompasses; *navigation, maintenance in the engine room, maintenance on deck, administration, responsibility, cargo conditioning* and *life support. Maintenance on deck, administration* and *cargo conditioning* could all be replaced without further technological development; however, thus far, this has not been done in practice. This is attributed to the lack of an economic benefit to moving these tasks ashore. Along the same lines, there is no economic benefit to moving *responsibility* ashore, while the captain and chief engineer remain on board. *Life support* cannot be replaced while a crew remains. This leaves navigation and maintenance in the engine room. Of these two, the *navigation* cluster has a higher TRL and shorter implementation time. Therefore, the *navigation*

Table 5.2: Required crew members per cluster, sorted by travel phase and per department

Cluster	Bridge department	Engine room department	Deck department	Total crew
LOADING AND UNLOADING PHASE				
Maintenance in engine room	0	1	0	1
Bunkering	0	2	0	2
Administration	2	1	1	4
Port supervision	0	2	2	4
Responsibility	1	1	0	2
Life support	0	0	1	1
ARRIVAL AND DEPARTURE PHASE				
Mooring	0	0	7	7
Navigation	2	0	0	2
Maintenance in engine room	0	1	0	1
Responsibility	1	1	0	2
NORMAL SAILING PHASE				
Navigation	3	0	1	4
Maintenance in engine room	0	2	0	2
Maintenance on deck	2	0	1	3
Administration	2	1	1	4
Responsibility	1	1	0	2
Cargo conditioning	0	0	2	2
Life support	1	0	1	2

Table 5.3: Summary of the selected logical concepts

	Required crew during Loading and unloading	Required crew during Arrival and departure	Required crew during Normal sailing	Crew cost reduction per month [€]
Base case	9	9	11	0
Concept 1: Partial replacement of navigation	9	9	8	5,600
Concept 2: Replacement of mooring and port supervision	6	3	8	16,400
Concept 3: Replacement of maintenance on deck, administration and cargo conditioning	5	4	5	33,400
Concept 4: Redistributing the cooking task	4	4	4	38,800
Concept 5: Replacement of near shore navigation, bunkering and moving responsibility to chief engineer	2	1	2	65,200
Concept 6: Replacing maintenance in engine room, responsibility and crew support	0	0	0	97,800

cluster will be removed first. In Chapter 4, two different solutions for automating the *navigation* cluster were suggested. In this case, the first, simpler, solution is used where only the *navigation* during the normal sailing phase is automated.

5.3.2. CONCEPT 2

This first reduction leads to two new critical phases, loading and unloading and arrival and departure, as can been seen in Table 20. For the loading and unloading phase, port supervision is selected to be replaced. This cluster is easy and relatively cheap to implement. For arrival and departure, the mooring cluster is replaced, as it has the highest TRL. As discussed in Chapter 4, mooring can be replaced by either a shore crew, or a fully automatic system. As a shore crew is likely to be a cheaper and simpler option, this solution is selected.

5.3.3. CONCEPT 3

As per Table 5.3, the critical phase for concept 3 is now normal sailing again, which requires 8 crew members. Out of the remaining clusters, maintenance on deck, administration and cargo conditioning have the shortest time to availability. These solutions can all be implemented with relative ease by a shore crew. While aiming to reduce the required crew during the normal sailing phase, the crew in the loading and unloading phase is also decreased as a consequence, as administration and maintenance on deck also take place in this phase.

5.3.4. CONCEPT 4

In concept 3, the crew has been reduced to a maximum of 5 crew members. Figure 5.10 (left) shows the crew members that remain. The first thing to note is the fact that the ship still has a full time cook on board. This seems excessive for such a small crew. The right side of Figure 5.10 shows that when it is assumed that all crew members have the skill to perform the task *prepare food and drink* and the required time for this task is reduced to 4 hours, a cook is no longer required.

5.3.5. CONCEPT 5

At this point, only a few clusters of tasks remain. These are; *maintenance in the engine room, responsibility, bunkering, life support* and the near shore sailing part of the *navigation* cluster. There are two critical phases, loading and unloading and normal sailing, each of which require 3 crew members. The cluster in the loading and unloading phase that is easiest and most likely the cheapest to replace is *bunkering*, especially since several other clusters have already been moved to shore. Therefore, this cluster is selected to be replaced. To reduce the size of the crew in the normal sailing phase, the remaining part of the *navigation* cluster is automated. It is believed that the technology to do this will be available sooner than a propulsion system that will not require human interaction. In order to fully remove the captain from the ship, the *responsibility* task is replaced as this is the captain's one remaining task on board. This means that a very small crew of 2 engineers remains.

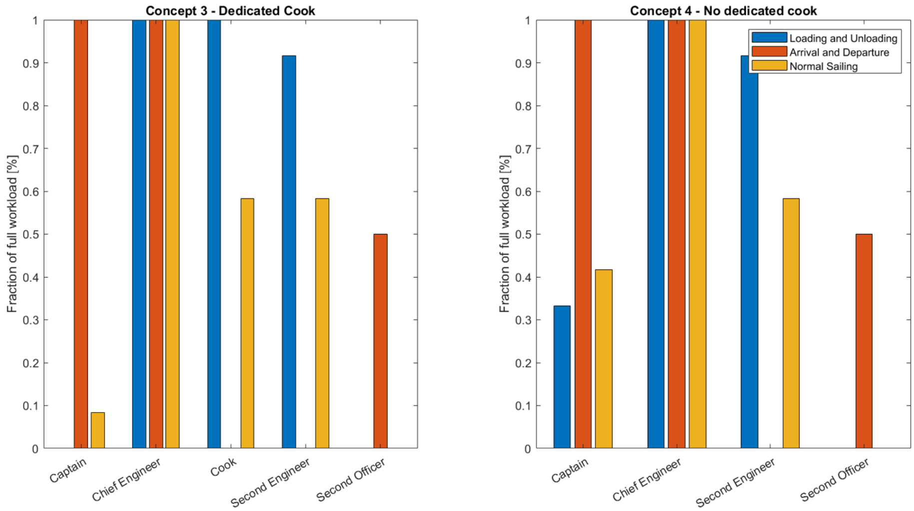

Figure 5.10: Left: workload for the remaining 5 crew members for each of the travel phases, right: workload with other crew members having the capability to prepare food.

5.3.6. CONCEPT 6

To make the final step in the crew reduction process, the *maintenance in the engine* room cluster needs to be replaced. Additionally, the regulations should allow someone to be responsible for a ship from a distance. If these two challenges are solved, the final remaining cluster, *life support*, is also no longer required. It should be noted that this last step is very expensive, since it requires the implementation of an elaborate shore control station as well as a new, expensive, power plant on board the ship.

5.3.7. PLACEMENT OF SELECTED CONCEPTS IN THE HEAT MAP

In Section 5.2.1 the assumption was made that simply selecting the concepts that lead to the largest decrease in crew cost would not always lead to workable results. Figure 5.11 shows that the selected concepts generally have a low number of clusters replaced for the number of crew members they require. Figure 5.12 shows where the selected concepts are located within the cost heat map. It shows that the selected concepts are not located at the bottom of the graph (where the cost reduction would be the largest). In many cases there are other concepts that would lead to a larger decrease in cost reduction, however these are not selected. This can be because it requires a replacement solution that is not currently available, or because the investment cost of that solution is deemed too high. The cost of the selected concepts remain high because the two engineers and the captain, who are relatively expensive, stay on board until removed in the last two clusters.

Number of replaced clusters \ Relaxed task assignment	Required number of crew members: 0	1	2	3	4	5	6	7	8	9	10	11
0	0	0	0	0	0	0	0	0	0	0	0	1
1	0	0	0	0	0	0	0	0	0	4	2	5
2	0	0	0	0	0	0	0	0	1	34	10	10
3	0	0	0	0	0	0	0	1	31	103	20	10
4	0	0	0	0	0	0	4	12	136	153	20	5
5	0	0	0	0	0	5	21	68	234	123	10	1
6	0	0	0	0	2	25	48	133	198	54	2	0
7	0	0	0	0	15	45	56	114	88	12	0	0
8	0	0	0	4	28	35	31	46	20	1	0	0
9	0	0	4	7	17	10	6	9	2	0	0	0
10	0	0	6	1	3	0	0	1	0	0	0	0
11	1	0	0	0	0	0	0	0	0	0	0	0
	1	0	10	12	65	120	166	384	710	484	64	32

Figure 5.11: Placement of the selected concepts in the heat map

Monthly crew cost in euro \ Relaxed task assignment	Required number of crew members: 0	1	2	3	4	5	6	7	8	9	10	11
> 90001	0	0	0	0	0	0	0	0	0	192	48	32
80001 - 90000	0	0	0	0	0	0	0	76	409	204	16	0
70001 - 80000	0	0	0	0	0	40	60	182	217	80	0	0
60001 - 70000	0	0	0	0	0	41	72	70	47	8	0	0
50001 - 60000	0	0	0	4	41	18	28	38	21	0	0	0
40001 - 50000	0	0	0	5	12	11	4	8	16	0	0	0
30001 - 40000	0	0	4	1	8	8	2	8	0	0	0	0
20001 - 30000	0	0	5	1	4	2	0	2	0	0	0	0
10001 - 20000	0	0	0	1	0	0	0	0	0	0	0	0
0 - 10000	1	0	1	0	0	0	0	0	0	0	0	0

Figure 5.12: Placement of the selected concepts in the cost heat map

5.4. ECONOMIC ANALYSIS

To determine the economic feasibility of autonomous ships, a cost-benefit analysis is performed for each concept found from the previous analysis. A key part of the input are the costs determined in Chapter 4. These are the additional costs that are incurred due to the changes that are made. However, the additional cost due to the replacement solutions do not give the whole cost picture. The replacement solutions influence, for example, the size of the crew and the stores, and additional systems have their own maintenance cost. To determine exactly which costs the changes to the ship and its organisation will influence, the standard cost breakdown of conventional ships is used.

For the analysis, the standard cost breakdown of a conventional ship is used. This breakdown is commonly used to analyse the different costs that a ship incurs in its lifetime (see, for example: [21, 43, 74, 93]. Not all cost aspects of a conventional ship are expected to change for each replacement solution. The first step is, therefore, to investigate which cost aspects are going to change when changes to the ship design are made. Next, the costs are quantified for each of the replacement solutions. Since several solutions are not commercially available yet, there is still uncertainty about their cost. As stated earlier, due to this inherent uncertainty, this thesis does not claim to present highly accurate cost calculations. It does, however provide values that are accurate enough to judge if a solution is significantly cheaper, significantly more expensive or approximately equally expensive as not replacing the affected task clusters, and thus if it is likely that a solution is economically viable.

5.4.1. THE COST STRUCTURE OF A CONVENTIONAL SHIP

The costs of a ship can be split up into several different elements. Some of these costs will change between a manned ship and an unmanned ship, and some will remain the same. To perform a cost-benefit analysis, only the factors that change are of interest. The cost structure of a conventional ship is investigated to find which factors will change.

For this work, the cost of operating and owning a ship is defined according to [80]:

$$C = OC + PM + VC + CHC + K$$

In which:
OC = Operating Cost (i.e., crew cost, stores, repair and maintenance and insurance)
PM = Periodic Maintenance Cost (i.e., interim dry-docking and special surveys)
VC = Voyage Cost (i.e., fuel costs, port and canal dues)
CHC = Cargo Handling Cost
K = Capital Cost (i.e., depreciation, interest)

The expected impact of manning reduction on these cost items, and the reasoning behind this can be found in Table 5.4.

CHANGES IN OPERATING COST

The operating cost are the cost of day to day operation of the ship. These costs are further split up according to [80]:

$$OC = M + ST + MN + I + AD$$

In which:
M = Manning
ST = Stores (i.e., Food and drink, lube oil)
MN = routine Repair and Maintenance
I = Insurance
AD = Administration Cost (i.e., management fees, registration cost etc.)

Figure 5.13 gives an overview of the distribution of these costs for conventional ships carrying a maximum of 999 TEU [55]. Using the crew cost as an input for the ship used in the case study, the costs can be determined.

The decrease in manning cost for each of the concepts is known, as it is part of the output from the CAA. It is assumed that the stores will decrease proportionally to the decrease in crew size. The changes to the operational costs are based on the percentages in Figure 5.13. In general, maintenance costs are estimated on the basis of the initial investment cost of the engine, number of running hours, installed power or cost of fuel (Stapersma, as quoted in [24]) on the total initial investment cost [1]. In this case, the total initial investment cost is used to calculate the maintenance costs for the suggested adaptations.

Table 5.4: Expected changes of the different cost factors

Cost item	Change expected?	Reasoning
Operating cost	Yes	As the size of the crew becomes smaller, the crew cost will decrease. Other costs, such as maintenance and repair and insurance will change due to newly installed systems and changed maintenance strategies.
Periodic maintenance	No	Costs for dry-docking and special surveys are assumed to be constant. Additional maintenance costs due to changes in maintenance strategy are covered under new costs for solutions to replace crew tasks.
Voyage costs	Only when the propulsion is changed	The routes and speed will not change, therefore the voyage costs will remain the same. While a smaller crew will lead to a lower auxiliary power use, this effect is deemed negligible. The weight of the ship is also expected to change. However, the effects of this on the fuel use has not been investigated. This research assumes that the weight and fuel consumption of the ship will not change with the suggested changes. A change in fuel cost is expected if another type of propulsion is selected. The fuel cost is assumed to remain constant for all other changes.
Cargo handling cost	No	The cargo capacity of the ship is assumed to be constant and the cargo is still handled with the same shore-side equipment.
Capital cost	Yes	New systems will increase investment cost, thus also increasing the depreciation, interest and insurance. For unmanned ships, the accommodation can be removed, saving on building costs.

The building cost of the ship can be calculated using the gross tonnage. From Figure 3.5 it is known that the ship has a gross tonnage of 7680 GT [**ConfeederShipping&Chartering**]. The building cost of the ship is calculated according to Martínez-López, Kronbak, and Jiang ([52]):

$$C_{Build} = -4 \cdot 10^{-8} \cdot GT^2 + (0.0029 \cdot GT - 2.5447)\frac{10^6}{1.29} = €15{,}292{,}500$$

Using the calculated maintenance cost from Figure 5.13 and the total investment cost, the percentage of maintenance cost can be calculated. This is 2.4% of the total investment. The administration cost for the ship will remain the same regardless of manning. Finally, the fuel cost will only change if there is a change in propulsion type.

ADDITIONAL COST OF CHANGING PROPULSION TYPES

In Chapter 4, two suggestions are made as alternatives to the conventional diesel engine that currently propels most ships; using multiple generators or using a PEMFC. Chapter 4 only detailed the difference in investment cost between the types of propulsion. However, there are more costs to consider when switching between propulsion types.

5

Cost factor	Yearly cost [€]
Crew cost	1,173,600
Maintenance and repair	356,400
Stores	168,000
Insurance	62,400
Administration	314,400
Fuel consumption	3,267,000

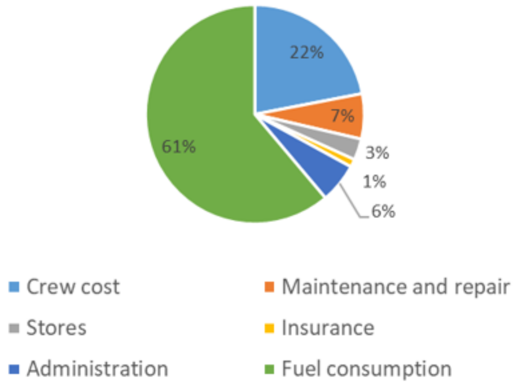

Figure 5.13: Yearly operational expenses [crew cost obtained from JR shipping, fuel cost calculated from [**ConfeederShipping&Chartering**] and MGO cost on March 12, 2021 and other percentages taken from [55]]

The reference ship is equipped with a 7200 kW strong medium speed diesel (see Table 5.5. Using the values in Table 5.5, the yearly fuel cost of the diesel engine and the multiple generators can be calculated at €3,267,000 per year. For the PEMFC, the fuel cost ranges between €3,569,200 and €8,111,900, dependent on the fuel price.

Using the information from the same table, the maintenance cost of the diesel engine and the diesel generators is €279,900 per year, assuming 24/7 operation at full power for all 180 active days. For the PEMFC, these costs range between €115,200 and €324,000. It is, therefore, assumed that the maintenance cost for these systems are comparable and they are not taken into account as a difference between the systems.

Table 5.5: Key costs of different propulsion types

Propulsion system	Maintenance cost per year	Fuel consumption	Fuel price
Medium speed diesel engine (7200 kW)	0.009 €/kWh (Hekkenberg, 2013)	33 t MGO / 24hr (Confeeder Shipping & Chartering, n.d.)	MGO 550 euro / t
PEMFC (7200 kW)	16 – 45 €/kW (Saito, 2018) I.e., 0.0037 – 0.01 €/kWh	$\frac{26{,}08}{500} \cdot P$ kg/hr (Saito, 2018) I.e., 9 t H_2 / 24hr	2200 - 5000 euro/t (KPMG Global, n.d.)
3 diesel generators (total 7200 kW)	0.009 €/kWh (Hekkenberg, 2013)	33 t HFO / 24hr (Confeeder Shipping & Chartering, n.d.)	MGO 550 euro / t

CHANGES IN THE CAPITAL COST

The capital cost are the obligations incurred due to investments to pay for the vessel. For this research, only the interest and depreciation are important. The addition of new systems to the ship will change the total investment cost of the ship and therefore the interest and the depreciation. The interest is set at 5% of the total investment annually.

For each of the systems that are installed, a lifetime is assumed, as mentioned in Chapter 4. This lifetime can be used to determine the depreciation of each of the newly installed systems. For this research, it is assumed that the value of the system reduces to zero, as the remaining value is unknown. By assuming that the remaining value of a system is 0, the worst case scenario is investigated. A linear depreciation is assumed, meaning that each year, the value of the system decreases with the same fraction.

For each of the engine types, the new cost for the power plant (i.e., fuel cells and supporting systems) is calculated (see Chapter 4. The additional depreciation cost per year is calculated by:

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$$Additional\_depreciation\_per\_year = \frac{Cost_{newpowerplant} - Cost_{Mediumspeeldiesel}}{Servicelife_{newpowerplant}}$$

5.5. COST-BENEFIT ANALYSIS

The final step is to perform a cost-benefit analysis on the selected concepts. The cost-benefit analysis is used to determine which of the selected concepts will decrease the overall cost of owning and operating the ship. While other arguments are used to sell the idea of unmanned and autonomous ships, economic viability is by far the most important. Investments are only made if the new concepts are at least the same cost as the conventional situation. The full cost benefit analyses for each of the concepts are given in tables 5.6 to 5.12.

Table 5.6: Overview of the change in annual costs and benefits for concept 1, best case

Cost		Benefits	
Depreciation	€ 16,000	Crew savings	€ 67,200
Maintenance	€ 1,900	Store savings	€ 30,500
Insurance	€ 300		
Interest	€ 4,000		
Total	**€ 22,200**	**Total**	**€ 97,700**
Difference	**€ 75,500**		

Table 5.7: Overview of the change in annual costs and benefits for concept 2, best case

Cost		Benefits	
Depreciation	€ 20,500	Crew savings	€ 196,800
Maintenance	€ 2,500	Store savings	€ 45,800
Insurance	€ 400		
Interest	€ 5,100		
Shore crew cost	€ 253,000		
Usage cost	€ 76,400		
Total	€ 357,900	Total	€ 242,600
Difference	€ - 115,300		

Table 5.8: Overview of the change in annual costs and benefits for concept 3, best case

Cost		Benefits	
Depreciation	€ 20,500	Crew savings	€ 400,800
Maintenance	€ 2,500	Store savings	€ 91,600
Insurance	€ 400		
Interest	€ 5,100		
Shore crew cost	€ 278,900		
Usage cost	€ 78,900		
Total	€ 386,300	Total	€ 492,400
Difference	€ 106,100		

Table 5.9: Overview of the change in annual costs and benefits for concept 4, best case

Cost		Benefits	
Depreciation	€ 20,500	Crew savings	€ 465,600
Maintenance	€ 2,500	Store savings	€ 106,900
Insurance	€ 400		
Interest	€ 5,100		
Shore crew cost	€ 278,900		
Usage cost	€ 78,900		
Total	€ 386,300	Total	€ 572,500
Difference	€ 186,200		

Table 5.10: Overview of the change in annual costs and benefits for concept 5, best case

Cost		Benefits	
Depreciation	€ 54,000	Crew savings	€ 782,400
Maintenance	€ 6,500	Store savings	€ 137,500
Insurance	€ 1,000		
Interest	€ 13,500		
Shore crew cost	€ 403,700		
Usage cost	€ 81,600		
Total	**€ 560,300**	**Total**	**€ 919,600**
Difference	**€ 359,500**		

Table 5.11: Overview of the change in annual costs and benefits for concept 6 with generators, best case

Cost		Benefits	
Depreciation	€ 11,400	Crew savings	€ 1,1173,600
Maintenance	€ -19,000	Store savings	€ 168,000
Insurance	€ -3,200		
Interest	€ -39,700		
Shore crew cost	€ 538,600		
Usage cost	€ 84,300		
Total	**€ 572,400**	**Total**	**€ 1,341,600**
Difference	**€ 769,200**		

Table 5.12: Overview of the change in annual costs and benefits for concept 6 with fuelcell, best case

Cost		Benefits	
Depreciation	€ 1,068,400	Crew savings	€ 1,173,600
Maintenance	€ - 41,500	Store savings	€ 168,000
Insurance	€ 58,700		
Interest	€ 734,300		
Shore crew cost	€ 538,600		
Usage cost	€ 84,300		
Additional fuel cost	€ 302,200		
Total	**€ 2,745,000**	**Total**	**€ 1,341,600**
Difference	**€ -1,403,400**		

5.5.1. ECONOMIC VIABILITY

In Table 5.3 6 different concepts, with varying crew requirements were identified. Using the cost-benefit method shown above and the cost structure of a conventional ship the total yearly cost of the concepts can be determined. This allows for an investigation of the economic viability of each of the concepts. A scenario is deemed economically viable if the monetary benefits outweigh the additional costs. This is determined by comparing the additional costs that are incurred due to selected solution and the additional OPEX with the savings that come from removing the crew and the savings on stores.

Table 5.13: Net benefit for the best and worst case scenarios

Concept	Total yearly cost [€]	Net benefit per year [€]	Cost change [%]
Base case	6,718,100		
Concept 1	6,642,600	75,500	-1.1%
Concept 2	6,833,400 to 6,982,700	-115,300 to -264,600	1.7% to 3.9%
Concept 3	6,612,000 to 6,784,600	106,100 to -66,500	-1.6% to 1.0%
Concept 4	6,531,900 to 6,704,500	186,200 to 13,600	-2.8% to -0.2%
Concept 5	6,358,600 to 6,613,100	359,500 to 105,000	-5.4% to -1.6%
Concept 6 Diesel generator	5,948,900 to 6,283,000	769,200 to 435,100	-11.4% to -6.5%
Concept 6 PEMFC	8,116,300 to 12,998,300	-1,403,400 to -6,280,000	20.9% to 93.5%

Table 5.13 gives the total costs and benefits for the scenarios. The table shows that concept 1,4 and 5 are worthwhile. Concept 2 is not economically viable. Concept 3 is only viable in the best case scenario. The viability of concept 6 is highly dependent on the chosen propulsion type. For concept 2, only a small reduction in crew is achieved, while some significant additional costs are incurred due to the requirement of on shore personnel. Therefore, this concept is left out of the assessment for here on out. The sixth scenario has a significant additional cost, which is mainly explained by the high cost of the PEM-Fuel cell and the potentially high cost of the fuel. Equipping the ship with diesel generators would make the scenario viable.

There is only a small difference between concept 3 and 4. In concept 4, the full time cook is taken off the ship, and their tasks are redistributed over the remaining crew members. This increases the benefit, without incurring additional cost. Therefore, in the rest of this assessment, only concept 4 is analysed.

5.5.2. DISTRIBUTION OF COST FACTORS

With the changes made to the organisational structure, the distribution of the OPEX factors also changes. Figure 5.14 shows the yearly cost for each of the concepts in the best case scenario (i.e., with the lowest additional cost). The total cost decreases until concept 6 with the fuel cell, where there is an increase. The main reason for the decrease of the total cost is in the decrease in the crew cost (i.e., crew cost and shore crew cost combined). For the final scenario, the increase in the investment cost due to the use of the fuel cell significantly increases the interest and depreciation. The fuel cost increase as well, but only by a small margin. This is explained by the significantly lower fuel consumption of the fuel cells. In the best case this offsets the higher price of the hydrogen. In the worst case this is a more significant difference.

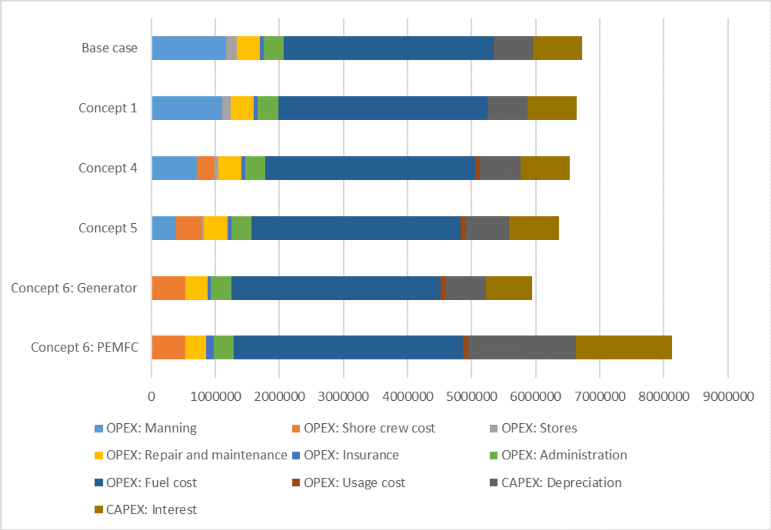


Figure 5.14: Distribution of cost factors best case scenario

In the worst case scenario, the differences between the first three scenarios and the reference ship are smaller (see Figure 5.15. This is mainly due to the higher shore crew cost, which reduces the effect of the lower on board crew cost. For the PEMFC concept, the main challenge is the increased fuel cost. While at its lowest price point, the cost of the hydrogen barely differs from the cost of the MGO (mainly due to the lower fuel consumption), at maximum cost, the hydrogen costs more than 2 times what the MGO costs.

5.6. SENSITIVITY OF THE RESULTS

In this section, the sensitivity of the results presented above is investigated. This is done by investigating the maximum possible change in the investment cost and in the total cost that is possible before each of the selected concepts changes from economically viable to not viable.

5.6.1. INCREASE OF INVESTMENT COST

The investment cost for the newly required systems have been estimated based on available data. In this part of the sensitivity study, the investment cost of the systems is increased until each of the concepts is no longer economically viable. This is done for both the best case scenario and the worst case scenario.

Table 5.14 shows that in the best case scenario the increase in the investment cost can be a minimum of 340%. This means that the cost of the navigation system can increase from €80,000 to €352,000 before the costs and benefits of the concepts become equal. For the worst case scenario, the costs can increase with a minimum of 48%, which means that a significant increase is still possible. This means that the investment cost of the new

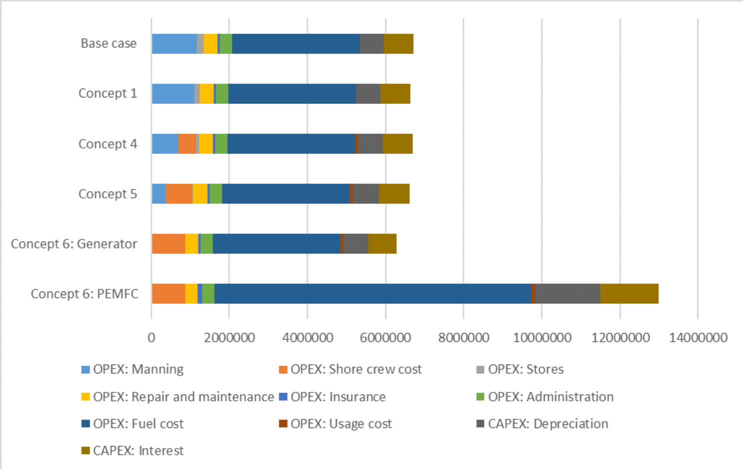


Figure 5.15: Distribution of cost factors worst case scenario

Table 5.14: Possible increase in investment cost without changing the viability of the concepts

Concept	Original investment cost [€]	Maximum investment cost best case scenario [€]	Maximum increase best case scenario	Maximum investment cost worst case scenario [€]	Maximum increase worst case scenario
Concept 1	80,000	352,000	340%	352,000	340%
Concept 4	102,500	772,300	653%	151,700	48%
Concept 5	269,900	1,565,400	479%	647,800	140%
Concept 6: Generator	1,205,900*	4,210,400*	415%	1,979,500*	235%

* This value does not include the savings that occur due to the removal of the accommodation, which have been estimated to be €2.000.000

systems is not a significant factor in the economic viability of low and unmanned ships.

5.6.2. INCREASE OF ALL COST

From the section above, it is known that the investment cost of the new systems is not a driving factor for the economic viability of the low and unmanned ship. Therefore, a second analysis is made where all the costs, i.e., shore crew cost, investment cost and usage cost, are increased by the same amount. The results of this analysis are shown in Table 5.15 for the best case and Table 5.16 for the worst case.

In the best case scenario, the total additional cost of each of the concepts can increase significantly. In the worst case scenario, this number drops down to only 2% for concept 4. This shows that this concept is the most sensitive to changes in the cost, and would be the first to switch from viable to not viable. However, in this scenario, higher crew costs are already assumed.

Table 5.15: Possible increase in investment cost without changing the viability of the concepts

Concept	Initial cost [€]	Maximum total cost [€]	Increase of total cost
Concept 1	80,000	352,000	340%
Concept 4	460,300	584,600	27%
Concept 5	755,200	1,238,500	64%
Concept 6: Generator	1,828,800	3,566,200	95%

Table 5.16: Possible increase in investment cost without changing the viability of the concepts

Concept	Initial cost [€]	Maximum total cost [€]	Increase of total cost
Concept 1	80,000	352,000	330%
Concept 4	632,900	648,700	2%
Concept 5	1,009,700	1,141,000	13%
Concept 6: Generator	2,162,900	2,995,600	38%

5.7. GENERALISATION OF THE RESULTS

The results presented above are based on the crew tasks and operational profile of the short sea container vessel *MV Endurance*. However, these results can be used to make more generalised predictions regarding the economic viability of reduced manning concepts for different ship types. In this section the effects of changing the number of port calls (i.e., the operational profile), the installed power and the size of the crew are investigated, thus enabling extrapolation of results to a large part of the world's fleet of cargo ships. For these analyses, only the values for the best case scenario are used.

5.7.1. PORT CALLS

The reference ship used in the case study above sailed for 3 days, after which 3 days were spend in port. To investigate the effects of the sailing for a longer period of time, i.e. on longer uninterrupted routes, a sailing time of 6 and 12 days is investigated. This means that the number of port calls drops to 40 and 24 per year.

With the decreased number of port calls, a number of other costs will also change. The mooring costs will drop to match the number of port calls. The cost of port supervision reduces, as the ship spend less time in port. Finally, the fuel cost changes with number of sailing days. This is only relevant for the final scenario. The maintenance costs are assumed constant. This means that the maintenance interval increases, but that more maintenance is performed while the ship is in port. The changing costs are given in Table 5.17.

Figure 5.16 shows the difference in benefit for each of the concepts as the number of port calls drops. It is clear that lowering the number of port calls is beneficial as the on shore costs drop. However, this does mean that the more time a ship spends at sea, the lower the port-related additional costs are. These lower port-related costs have a positive

Table 5.17: Changing costs with fewer port calls

Cost factor	Crew cost for 60 port calls per year [€]	Usage cost for 60 port calls per year [€]	Crew cost for 40 port calls per year [€]	Usage cost for 40 port calls per year [€]	Crew cost for 24 port calls per year [€]	Usage cost for 24 port calls per year [€]
Mooring		60,000		40,000		24,000
Port supervision	253,000 – 402,300	22,500	126,500 – 201,200	22,500	63,200 – 100,600	22,500

effect on the benefit of the case.

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6: Generator	Concept 6: PEMFC
60 port calls	€ 75,500	-€ 115,300	€ 102,400	€ 182,500	€ 354,100	€ 763,800	-€ 1,408,800
40 port calls	€ 75,500	-€ 10,900	€ 206,800	€ 286,800	€ 460,200	€ 869,800	-€ 1,403,600
24 port calls	€ 75,500	€ 72,500	€ 290,200	€ 370,300	€ 543,600	€ 953,300	-€ 1,320,100

Figure 5.16: Differences in benefit for the best case given different port calls for each of the concepts

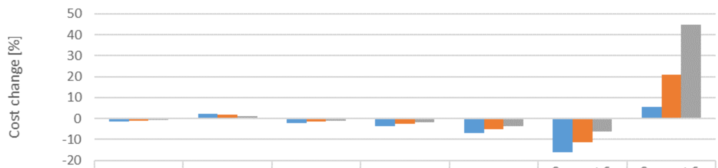
5.7.2. INSTALLED POWER

The installed power mostly affects the absolute savings in the final concept, where it is by far the largest influence on the economic viability. However, when savings of the concepts are expressed as percentages of the total cost, there will be changes for all concepts, as the cost of the base case changes. The reference ship is equipped with a power of 7,200 kW. In this section, the effects of sailing with a lower and a higher power are investigated. In this case, the effect of sailing with an installed power of 3,600 kW and 14,400 kW. Table 5.18 shows the investment cost for each of the different propulsion types at the different levels of installed power.

Table 5.18: Cost overview for different installed power for the diesel engine, the diesel generators and the PEMFC

	Cost for 3,600 kW [€]	Cost for 7,200 kW [€]	Cost for 14,400 kW [€]
Diesel engine	792,000	1,584,000	3,168,000
Diesel generators	1,260,000	2,520,000	5,040,000
PEMFC	9,000,000	18,000,000	36,000,000

The specific fuel consumption (sfc) of the engine in the reference ship is given as 33 t/24 hours, or 191 g/kWh. Different sized engines might have a different sfc. The fuel consumptions for the smaller and bigger engine are based on Wärtsilä engines of the same approximate size. This results in a sfc of the 3,600 kW of 190 g/kWh [85] and a sfc of 175 g/kWh for the large engine [86]. The fuel consumption for the fuel cell is kept proportionally to the installed power, as given in Table 5.5. The results of this analysis are given in Figure 5.17 and Table 5.19.



	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6: generator	Concept 6: PEMFC
3,600 kW	-1.5	2.3	-2	-3.6	-7	-16.2	5.4
7200 kW	-1.1	1.7	-1.5	-2.7	-5.3	-11.4	20.9
14,400 kW	-0.8	1.2	-1.1	-1.9	-3.8	-6.4	44.9

Figure 5.17: Cost change in percentage for 3,600 7,200 and 14,400 kW installed power

Table 5.19: Distribution of total investment cost for three different levels of installed power for the best case scenario

	Total yearly cost 3,600 kW [€]	Total yearly cost 7,200 kW [€]	Total yearly cost 14,400 kW [€]
Base case	5,084,900	6,718,600	9,986,000
Concept 1	5,009,400	6,643,000	9,910,700
Concept 2	5,200,100	6,833,900	10,101,400
Concept 3	4,982,400	6,616,200	9,883,600
Concept 4	4,902,300	6,536,000	9,803,600
Concept 5	4,729,000	6,362,800	9,630,300
Concept 6: generator	4,264,100	5,953,000	9,331,000
Concept 6: PEMFC	5,350,200	8,125,300	13,675,400

The results show that a smaller installed power is beneficial for the cost savings, when expressed as a percentage of the total cost. The percentage of cost savings increases when the total installed power decreases due to the simple fact that fuel consumption is proportionally lower and thus makes up a smaller percentage. For the unmanned concept with the fuel cell, the changes in the total cost are the most significant, from 44,9% more expensive to 5.4% more expensive. This is explained by the increasing cost of the fuel cell and the lower cost of fuel for diesel engine compared to the fuel cell.

In general this means that ships with a larger installed power are less favourable for low manned and unmanned sailing than ships with a smaller installed power. For ships with a very low power requirement, (i.e., <2,750 kW) the unmanned variant with the fuel cell could be beneficial compared to a manned diesel powered ship of the same size.

5.7.3. CHANGES IN CREW SIZE

The final generalisation that is made in this thesis is a change in the crew cost. The economic viability of each of the concepts is dependent on the cost savings that are possible due to the removal of the crew. For that reason, the effects of a significantly larger and smaller crew are investigated. For a detailed analysis for a specific ship, the whole process explained in this thesis has to be repeated with the task distribution of that ship. However, assuming the tasks remain largely the same for smaller and larger ships, an rough assessment of the economic viability of possible.

In this analysis, the bulk carrier that is used as a case study in the MUNIN project is used [43]. The documentation of the project provides detailed information regarding the size of the ship and the composition of the crew, making a comparison with the reference ship of this dissertation possible. Table 5.20 shows some of the key particulars of the ship, and Table 5.21 compares the crew of the bulk carrier and that of the *MV Endurance*.

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Table 5.20: Key particulars of the MUNIN bulk carrier [43]

Ship dimension	Value
L_{oa}	230 m
B	32 m
Installed power	10,230 kW
Building cost	€ 28,500,000

There are a few key differences between the two crews. To start, the crew of the larger ship has more crew members in each department, but especially in the engine room department. On a large ship, a captain is not part of the watch keeping crew and therefore does not perform any navigation related tasks during the normal sailing phase. That means a third officer is required to take over his tasks.

The size of the deck department does not differ greatly between the two ships. However, the *Endurance* is a container ship, which comes with additional tasks for the deck department in terms of cargo conditioning. On a bulk carrier this task is also performed, albeit on a much smaller scale. On the other hand, the size of the tasks regarding general upkeep and maintenance of the ship is much larger.

The largest difference is the size of the engine room crew. The size of the crew on the bulk carrier is significantly larger. One of the reasons for that could be that the deck crew on the*MV Endurance* assists in the engine room when required, without having specific crew members assigned to the engine room permanently. Additionally, the difference in the size and type of engine and type of fuel (HFO instead of MDO) could also have an effect on the required crew.

Using the concepts that have been determined earlier, a corresponding crew reduction for the larger ship can be set up. The assumed crew reduction for each of the con-

Table 5.21: Crew composition used in MUNIN report for large bulk carrier [44], crew cost obtained from JR shipping

Crew member	Cost for operation company per month [€]*	Number of crew members on board of the *MV Endurance*	Number of crew members on board of large bulk carrier
Bridge department			
Captain	9,000	1	1
Chief officer	7,500	1	1
Second officer	4,200	1	1
Third officer	2,800		1
Engineering department			
Chief engineer	8,900	1	1
Second engineer	7,400	1	1
Third engineer	4,100		1
Fourth engineer	2,800		1
Electrician	5,000		1
Fitter	2,400		2
Motorman	2,000		2
Deck department			
Bosun	2,400	1	1
Cook	2,700	1	1
Able bodied seaman (ABS)	2,000	2	3
Ordinary seaman (OS)	1,800	1	1
Deck boy	1,400	1	
Steward	4,000		1
Total		**11**	**20**
Total Cost [€]		**97,800**	**154,800**

* The crew cost used in this table are the crew costs obtained from JR shipping to keep consistency in this dissertation. The cited MUNIN report uses their own estimation of the crew cost, but these differ from the cost used in this dissertation.

cepts can be found in Table 5.22. Due to the large number of remaining crew members, the cook is not removed from board, as providing meals for 12 crew members is a full time job.

The changes of the replacement solutions will largely remain the same. Only the costs of the on shore engineering crew will increase. In Section 4.2.3 the cost of the on shore maintenance team is set to be equal to the size of the engine room crew. For this ship, that means that the cost of that team will be €219,000 per year. For the short sea container vessel this was €114,600.

As the other replacement costs remain the same, having a larger crew proves to be beneficial. However, the bulk carrier also has a larger installed power, which is less favourable (as discussed in section 5.7.2). On the other hand, large bulk carriers generally sail longer distances and have a small number of port calls, which is more favourable (as discussed in section 5.7.1). Additionally, a higher building cost also increases the

Table 5.22: Reduction of crew members for a larger ship

	Removed crew members	Required crew	Cost reduction per month [€]	Cost reduction per month *MV Endurance* [€]
Base case		20	0	0
Concept 1	Second officer, third officer, OS	17	17,600	5,600
Concept 2	ABS	16	21,600	16,400
Concept 3	ABS, ABS, Chief officer	13	44,600	33,400
Concept 4	Steward	12	52,600	38,800
Concept 5	Bosun, Captain	11	75,400	65,200
Concept 6	All remaining crew members	0	154,800	97,800

maintenance cost of the ship. This means that generally having a larger crew is more favourable, but other operating parameters can influence the result.

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The reference ship is at the lower end of the number of crew members that can be on board of a ship. The total number of required crew members for sea going cargo vessels can drop to around 8, but not much lower. This means that, with regards to the crew, almost every sea going cargo vessel is suitable for low manned and unmanned sailing.

5.7.4. WORLDWIDE DIFFERENCE IN MANNING COST

In this dissertation the crew cost and wages of a Dutch company are used to determine the crew cost. However, the cost of manning a ship varies significantly dependent on where a ship is registered and where the crew comes from. Figure 5.18 shows the different cost of a captain, a chief engineer, a bosun and an ABS for a Dutch crew (high wages) on a Dutch ship, a Russian crew (medium wages) and an Algerian crew on an Algerian ship (low wages). As the largest savings for low manned and unmanned shipping comes from the crew cost, this is an area that requires further investigation. A ship crewed by an Algerian crew costs less than 20% of the cost of the Dutch crew used in this research. That would mean that all concepts proposed in this research would not be economically feasible. This means that a significant part of the world fleet, especially ships registered under the so called flags of convenience, would not benefit from low manned and unmanned ship concepts, especially if the ship calls at ports where the shore crews that are used to replace the crew members are not as cheap. Ships that are feasible are ships with a highly paid crew, for example sailing short sea shipping routes or performing specialised tasks in Europe, where the salaries are high.

5.8. CHAPTER SUMMARY

In this chapter, the final research question is adressed: *What ship and manning concepts are likely candidates for the development path towards unmanned ships?*. To answer this question, a method is set up to generate many different ship and manning concepts.

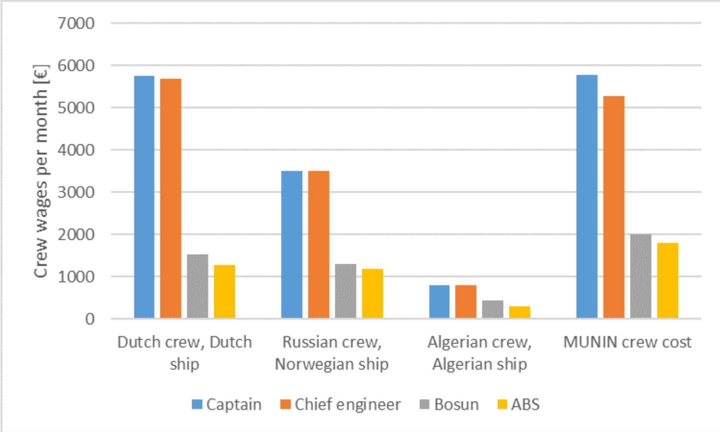

Figure 5.18: Different crew wages for different flag state and manning situations. Dutch wages from JR Shipping, MUNIN crew cost from [44], other cost from [78].

Additionally, this chapter introduced a method which can be used to select likely low manned ship concepts from a large selection. By using this method, a total of 6 plausible concepts were identified. From this analysis, two conclusions can be drawn:

- The relaxed task assignment results in smaller crews when clusters are replaced.
- There are many concepts that are likely to lead to limited savings as they have a limited effect on the crew size

A cost-benefit analysis is performed on 6 selected concepts. Out of these 6 concepts, 4 are beneficial over the base case with a manned situation. A sensitivity study is performed to check the robustness of the results. In the best case scenario, both the investment cost and the total cost of the replacement solutions can change significantly, a minimum of 340% and 27% respectively, without the concepts becoming more costly than the base case. For the worst case scenario, these values are lower.

Finally, a generalisation of the results towards the world fleet is performed. This generalisation shows that the following situations gives the following conclusions:

- Ships with fewer port calls have a larger potential benefit than ships with more port calls. A lower number of port calls lowers the cost of the onshore personnel required, which is a significant cost factor
- Ships with a lower installed power have a higher potential percentagewise savings and ships with a higher installed power have a lower potential percentagewise saving.
- The size of the engine room crew determines how many crew members remain on board before the final concept.
- Ships with a larger crew have a higher savings potential and thus percentagewise saving.

- Ships with a high wage crew are more beneficial than ships that sail with a low wage crew. Ships sailing with a low wage crew might not be suited for low manned and unmanned sailing, especially if the shore crew is not paid low wage.

6

Conclusion and discussion

In this chapter, the research questions are answered and the final conclusions are drawn. Each research question is answered individually, after which an evaluation is made regarding how well the goal has been reached. After that, a discussion of the results, the scientific contributions of this dissertation and suggestions for further research are given.

6.1. Conclusions

In this section, each of the research sub-questions is answered. In addition to that, the key findings of each chapter are mentioned.

What is the role of the crew in the fulfilment of the functions of the ship?

The first research question is answered in Chapter 2 by setting up a functional breakdown of the ship and a task breakdown of the crew though a combination of a field study and expert interviews. It was found that crew members are involved in practically every function of the ship. This also means that the crew performs a wide variety of tasks on board. Many of these tasks require physical interaction between the crew member and the ship, for example by performing maintenance or by refastening the cargo. The crew is very versatile and in many ways a very useful 'set of tools' to have on board.

Over the course of the research, to answer this question several other important findings were made:

- The journey of a ship can be split up into three distinct travel phases, the arrival and departure phase, the normal sailing phase and the loading and unloading phase. These phases each have their own crew requirements.
- There is a strict hierarchy on board. The tasks that a crew member performs are very much related to their rank.
- There are many individual tasks, but it is possible to cluster the tasks together to form 11 clusters;

- Open water navigation
- Near shore navigation
- Mooring
- Maintenance on deck
- Maintenance in the engine room
- Bunkering
- Administration
- Cargo conditioning
- Port supervision
- Crew support
- Responsibility

How can the effect of replacing tasks on the composition of the crew be determined?

In Chapter 3 it is explained that the challenge of assigning tasks over differently skilled crew members is mathematically defined as an assignment problem. In short, there are four ways an assignment problem can be solved; an exact method, a heuristic method, a metaheuristic method or simulation. Out of these methods, a heuristic method, the greedy algorithm, is deemed most appropriate for the problem at hand and is therefore selected. The greedy algorithm has the benefit of being based on logical choices, as opposed to simulation for example, and is therefore easy to follow and to understand. Additionally, it is quick and relatively simple to program. The largest downside of the greedy algorithm is that sometimes it finds a local optimum instead of the global optimum. To counteract that, several methods are applied to increase the likelihood of the algorithm resulting in a globally optimal solution. First, the tasks are sorted from most expensive to cheapest. Second, additional constraints are added to the algorithm to ensure that crew members are assigned as full a workload as possible and that narrow down which crew member can perform which tasks.

6

To test the algorithm, a case study is performed. In this case study, the following key observations were made:

- Only automating navigation-related tasks alone results in a small reduction of crew. Only a total reduction of 2 crew members, one of which a deck boy, is achieved. The crew members whose workload is most effected by the reduction of the navigation tasks also have other tasks that cause them to remain on board. This causes the algorithm to assign them tasks of lower ranking crew members to ensure a full workload.
- The strict hierarchy on board, where crew members only perform tasks within their department severely limits the effect of partial automation. On board of a conventional ship, each department has their own tasks and tasks are generally not transferred between departments. Additionally, crew members perform different tasks that are not necessarily part of the same cluster. This means that when the tasks for one department are reduced, only the workload of that department is reduced and in many cases the crew members remain. This results in a low decrease in crew. By allowing tasks to be transferred between departments if the

crew members have the required skill, the workload of the remaining crew members can be kept high. This causes a higher reduction in the number of required crew members. In this study, this is referred to as the relaxed task assignment.

What technically feasible options are available to replace the tasks on board? And what are the costs associated with these options?

In Chapter 4, a replacement solution is found for each of the 11 task clusters identified in Chapter 2. There are three types of solutions that are possible to replace a task cluster:

- A technical solution
- An organisational solution
- A solution where a service is hired

For each of the clusters, the costs of the different available solutions was investigated using literature. An overview of the most promising and economically favourable solutions is given in Table 6.1, which is also presented in Chapter 4.

Table 6.1: Summary of the required crew members per travel phase and situation

Cluster	Additional investment cost [€]	Yearly shore crew cost [€]	Yearly usage cost [€]
Mooring – shore based system	-	-	60,000
Open water navigation	80,000	-	-
Near shore navigation	167,400	123,100 – 195,700	2,700
Maintenance in the engine room – PEMFC	18,000,000	134,900 – 214,500	2,700
Maintenance in the engine room – generators	2,520,000	134,900 – 214,500	2,700
Maintenance on deck	-	13,300 – 29,200	-
Bunkering	-	1,700 – 11,000	-
Administration	-	12,600 – 20,000	2,500
Port supervision	22,500	253,000 – 402,300	-
Responsibility	-	-	-
Cargo conditioning	-	-	-
Crew support	-	-	-
Design changes	-	-	-2,300,000

What ship and manning concepts are likely candidates for the development path towards unmanned ships?

This question is answered in Chapter 5. There are several ways to identify possible design concepts. In this research, the concepts were generated using scenario building theory, specifically the normative method. The normative method uses a predefined starting point, i.e., the conventional ship, and a predefined end goal, in this case the unmanned ship, as guidelines along which to generate scenarios. The concepts are created by systematically replacing each of the task clusters defined in Chapter 1, leading to 2046 concepts between the conventional ship and the unmanned ship. The CAA introduced in Chapter 3 is used to define the required crew members for each of the concepts. The outcome of the analysis of the concepts is given in Figure 6.1 and Figure 6.2.

The heat maps presented in Figure 6.1 and Figure 6.2 show that there are many different ways to develop a ship concept that requires a certain number of crew members and that automating a given number of clusters can lead to a wide range of required crew members. Additionally, there are many concepts for which the crew cost is only reduced by a small margin. This shows that selection criteria are needed to identify which of the concepts are worth looking into further.

Relaxed task assignment — Automated clusters \ Required crew	0	1	2	3	4	5	6	7	8	9	10	11
0	0	0	0	0	0	0	0	0	0	0	0	1
1	0	0	0	0	0	0	0	0	0	4	2	4
2	0	0	0	0	0	0	0	0	5	26	8	6
3	0	0	0	0	0	0	0	3	40	61	12	4
4	0	0	0	0	0	0	4	27	103	67	8	1
5	0	0	0	0	0	5	24	68	116	37	2	0
6	0	0	0	0	4	22	40	71	63	10	0	0
7	0	0	0	2	13	31	22	34	17	1	0	0
8	0	0	3	5	13	10	4	8	2	0	0	0
9	0	0	5	1	3	0	0	1	0	0	0	0
10	1	0	0	0	0	0	0	0	0	0	0	0
	1	0	8	8	33	68	94	212	346	206	32	16

Figure 6.1: Heat map of the different concepts in the traditional task assignment

All phases — Monthly crew cost in euro \ Clusters removed	10	9	8	7	6	5	4	3	2	1	0	
> 90001	0	0	0	0	1	8	28	44	32	10	1	124
80001 - 90000	0	0	0	5	35	97	112	60	12	0	0	321
70001 - 80000	0	0	4	29	84	102	62	16	1	0	0	298
60001 - 70000	0	0	4	24	49	37	8	0	0	0	0	122
50001 - 60000	0	1	11	40	36	7	0	0	0	0	0	95
40001 - 50000	0	1	11	13	3	1	0	0	0	0	0	29
30001 - 40000	0	2	9	8	2	0	0	0	0	0	0	21
20001 - 30000	0	4	6	1	0	0	0	0	0	0	0	11
10001 - 20000	0	1	0	0	0	0	0	0	0	0	0	1
0 - 10000	1	1	0	0	0	0	0	0	0	0	0	2

Figure 6.2: Heat map of the different concepts in the traditional task assignment

From this analysis, the following conclusions can be drawn:

- In general, the relaxed task assignment results in smaller crews when clusters are replaced. Therefore, the relaxed task assignment should be implemented as soon as any cluster of tasks is replaced.
- There are many concepts that are likely to lead to limited savings as they have a limited effect on the crew size

Not all of the concepts are worth considering for multiple reasons. To identify the

Table 6.2: Summary of the selected logical concepts, applicable for the selected reference ship

	Required crew during Loading and unloading	Required crew during Arrival and departure	Required crew during Normal sailing	Crew cost reduction per month [€]
Base case	9	9	11	0
Concept 1: Partial replacement of navigation	9	9	8	5,600
Concept 2: Replacement of mooring and port supervision	6	3	8	16,400
Concept 3: Replacement of maintenance on deck, administration and cargo conditioning	5	4	5	33,400
Concept 4: Redistributing the cooking task	4	4	4	38,800
Concept 5: Replacement of near shore navigation, bunkering and moving responsibility to chief engineer	2	1	2	65,200
Concept 6: Replacing maintenance in engine room, responsibility and crew support	0	0	0	97,800

best order in which to replace clusters, and thus which concept is selected as worthwhile, the following selection steps are taken:

1. The clusters that are removed all take place in the normative phase of the voyage (i.e., the phase that requires the most crew members). Removing crew members from another phase will not lead to a reduction of the required crew.
2. The economic impact of the clusters is investigated. Scenarios will only be considered if it is likely that there is potential for an economic benefit for the ship owner. This is not a full economic analysis but based on the estimated implementation cost of the clusters as determined in Chapter 4.
3. Of the remaining clusters, the replacement options with the highest TRL or the shortest time to maturity time are selected.
4. The cluster with the highest impact on the size of the crew is selected.

After the first cluster is selected, the process is repeated until no clusters remain. The case study results can be found in Table 6.2.

The economic viability of each of the concepts is determined using a cost-benefit analysis. The result of this cost-benefit analysis can be found in Table 6.3. Out of the selected concepts, concept 2 and concept 6 with the fuel cell are not economically viable. In addition to that, the only difference between concept 3 and 4 is the removal of the dedicated cook, which requires no changes that cost money. Concept 4 results in significantly higher savings per year. For that reason, concepts 2 and 3 are not deemed worth considering as viable intermediate steps. Concept 6 is not viable with a fuel cell, but is viable when using multiple diesel generators as propulsion. A sensitivity study has shown that the results are very stable and large cost increases are required to change the viability of the concepts from viable to not viable.

Table 6.3: Net benefit for the best and worst case scenarios

Concept	Total yearly cost [€]	Net benefit per year [€]	Cost change [%]
Base case	6,718,100		
Concept 1	6,642,600	75,500	-1.1%
Concept 2	6,833,400 to 6,982,700	-115,300 to -264,600	1.7% to 3.9%
Concept 3	6,612,000 to 6,784,600	106,100 to -66,500	-1.6% to 1.0%
Concept 4	6,531,900 to 6,704,500	186,200 to 13,600	-2.8% to -0.2%
Concept 5	6,358,600 to 6,613,100	359,500 to 105,000	-5.4% to -1.6%
Concept 6 Diesel generator	5,948,900 to 6,283,000	769,200 to 435,100	-11.4% to -6.5%
Concept 6 PEMFC	8,116,300 to 12,998,300	-1,403,400 to -6,280,000	20.9% to 93.5%

The final step of this analysis is to extrapolate the results of the case study to the world fleet. For this, the effect of the number of port calls a ship makes, the installed power and the size of the crew are varied. This analysis showed that making fewer port calls is beneficial to the viability of both low manned and unmanned shipping. The cost of the on shore crew during port calls is significant and has a large influence on the total benefit. Having a lower installed power causes a larger percentagewise saving compared to a higher power. In general having a larger crew is more favourable than having a smaller crew.

6.1.1. ACHIEVEMENT OF RESEARCH GOAL

In Chapter 1, the following research goal was set up: *To identify technically feasible and economically viable ship and manning concepts that are on the likely development path towards unmanned ships.* The summary of the research questions above shown that there are multiple technically and economically viable ship and manning concepts that could be selected. Therefore, it can be concluded that the research goal has been reached.

6.2. SCIENTIFIC CONTRIBUTION

This section summarises the scientific contributions of this thesis. Research into unmanned and autonomous ships generally focusses on a few key sections of autonomous ships such as navigation and the shore control station or the propulsion of the ship. This is the first study that employs a systematic approach to ensure that all tasks that the crew perform are also executed in some way for unmanned and autonomous ships.

- *This study presents a task based analysis which allows for the identification of feasible and viable ship and manning concepts for low-manned and unmanned ships.* In current research, the focus is on the technical and economic viability of fully unmanned ships but none explicitly address all the tasks performed by the crew. This study ensures that all functions of the ship can still be fulfilled for low-manned concepts by starting with a functional breakdown and task breakdown of the ship.
- *The second contribution is the method to identify logical and feasible design concepts.* This dissertation is the first to focus on likely low manned ship concepts in addition to unmanned concepts. The most likely low manned concepts are selected by systematically analysing all concepts and making a selection. Currently, automation is generally added on an availability basis, but this research has shown that there is a significant possibility that doing this will result in increased cost, without benefits from removing crew members. By analysing which manning concepts show the most promise, a strategy can be made regarding the implementation of low manned ships and the corresponding investments.
- *The final contribution is the detailed analysis of the economic feasibility of the low manned and unmanned concepts.* Only a few academic articles have looked into the economic viability of unmanned ships, and none have looked into the economic viability of low manned ships. As money is the most important driver for commercial application of low manned and unmanned ships, the economic analysis is a key part of any research into new technologies. This research has shown that not all identified manning concepts are viable for a short sea container vessel, but there are several that are viable. The economic viability of the unmanned concept depends on the investment cost of the selected propulsion.

To summarise, the process developed within this research (See Figure 1.3) allows for systematic selection of low manned and unmanned ship concepts and an analysis of their economic viability. The process is applicable to all ships that have tasks that are unscheduelled and not bound to a specific time, as long as the input is varied to reflect the reference ship. Other ship types might require different solutions to some tasks, but that does not change the general proces. The proces can be used at different stages of a ship's life. it can be used during the design phase of a ship during which an analysis is made of the effects changes might have on the required crew. It can also be used to determine the effects of changes made during the life of the ship.

6.3. DISCUSSION

This discussion addresses three elements of this research; the design process and selected design methods, the economic analysis, and finally the societal feasibility of the results. This section ends with an overview of further research potential.

6.3.1. DESIGN PROCESS

The design process that is introduced in this research is broadly applicable and can be applied to many ship types. However, the results of one case study cannot be translated directly to other ship types since the results are highly dependent on the tasks that are done on board. Extrapolating the results for a larger or smaller ship of the same type, is possible from the results of the case study, as was shown in Chapter 5. However, for different ship types, the method is still valid but the input needs to be revised to match the new case.

In this study, the scheduling of tasks is left out of the algorithm. This is possible due to the nature of the tasks on board of a merchant ship. These tasks are not time sensitive, nor are they very complex, in the sense that they do not need many people performing subtasks in a specific order. Therefore the algorithm is capable of finding a feasible solution without scheduling tasks within a travel phase. However, this method is not suitable to be used on board of ships that do have these complicated tasks, such as working vessels or navy ships. For these types of ships, discrete event simulation is more suitable.

6.3.2. ECONOMICS

The cost-benefit analysis is mainly based on estimations of the costs. The sensitivity study shows that the costs can increase by a significant margin while the concepts remain viable. To improve the accuracy of the outcome of the cost-benefit analysis it should be updated as better cost assessments become available. Additionally, investment costs of new technical solutions are expected to reduce once the technology becomes more mature. These changes should also be taken into account in future assessments.

In this research, a cost-benefit calculation is only performed for the selected concepts. To check if the correct concepts have been chosen a detailed cost-benefit analysis of all concepts could be performed. This calculation can be used to ensure that the selection method of the concepts works as intended and no viable concepts are skipped. However, this would mean that 2048 cost-benefit analyses must be performed.

The final important aspect of the economic viability of the concepts discussed in this dissertation is the crew cost. As discussed in Section 5.7.4 the salaries used are relatively high. In many cases the salaries are much lower, which in turn lowers the cost savings when crew members are removed from the ship. Performing the calculations in this research with a lower total crew cost can change the results.

6.3.3. SOCIETAL FEASIBILITY

The final element addressed in this discussion is the societal feasibility. Acceptance by not only the people involved but also the general public is the final step of successful introduction of low manned and unmanned ships. It has not been addressed in this research, as the focus of this research is the economic viability of the selected concepts. However, as the research addresses the removal of crew members from the ship, the societal feasibility of the research cannot go unmentioned.

In this research, one of the aims of the greedy algorithm was to keep the workload of the remaining crew members as close to full time as possible. Doing this ensured that the smallest crew possible is on board, but will have effects on the jobs that each of the crew members performs. Performing tasks that are not assigned to the rank of the crew members and do not correspond with their training could negatively impact their work enjoyment. To combat this, the crew would need to be retrained to ensure that all crew members work at their own level.

In addition to a lower enjoyment of work due to changing responsibility and task assignment, the size of the crew can also have an impact. In the case study, the required number of crew members is reduced down to two, before the final step towards unmanned ships is taken. However, due to both emotional and physical safety, two crew members might not be enough. This would mean that the final clusters all need to be replaced together, instead of in two steps. Further research into the willingness of the crew to change the tasks they perform is also required. This research has shown that letting go of the traditional task assignment is a vital part of reducing the size of the crew. However, this would fundamentally change the work that is performed by certain crew members. How this will affect them has not been researched.

Not only the crew members of the ship and the maritime industry need to accept low manned and unmanned ships, the general public needs to accept them too. At this point, there is a lot of scepticism regarding specifically unmanned ships. For a successful implementation special attention has to be paid to address this scepticism.

6.3.4. Further research

There are several areas in which this research should be continued. Firstly, it would be beneficial to run the entire process presented in this thesis for different ship sizes and ship types. Section 5.7 provided some insight into the effects of changes to the case study ship. The results can be verified by adapting the input to match the different ships. That way, it is possible to draw more generalised conclusions.

A more general area that requires further investigation are the tasks of the shore control centre (SCC) crew. The assumptions used in this dissertation, i.e., one operator can observe six ships at the same time, have not been extensively validated in research. It is therefore not known if it is possible, and safe, for SCC personnel to monitor that many ships at the same time. Additionally, it is unknown how well operators would be able to solve problems and navigate the ships from a remote location. Further research in both the technical and the operational workings of the SCC are therefore required.

Along the same lines, an investigation of sailing with a small crew for longer periods of time need to be investigated. In this research, very small crews are suggested in the later concepts. However, generally crews are on board for periods between three and six months. The willingness of the crew to work in such an environment as well as any potential consequences on their (mental) health require further investigation.

Finally, more research is required into the reliability of new, steady state propulsion types such as fuel cells and batteries running at representative powers for longer periods of time. In research, it has been suggested that a single diesel engine is not suitable for unmanned sailing. This research has shown that sailing with diesel electric propulsion with multiple generators is a solution. However, this solution might be temporary. With the increased awareness of the greenhouse gas emissions produced by ships and the tightening of the emission guidelines other types of propulsion might become obsolete. A fast improvement of the capabilities and the cost of these steady state propulsion types might also increase the implementation of unmanned autonomous ships.

Acknowledgements

A little over 5 years ago, I was about to start my master thesis. If asked what I wanted to do after I finished I would have answered that I was unsure but wanted to move back to the North of the country. Halfway through my thesis I got offered this PhD position. I was enjoying doing my research but had never given doing a PhD much thought. Doing a PhD was something for the very smart people who locked themselves in their office for four (or more) years and came out with a book. However, my father convinced me that it might be a good fit; he was right.

When I started my PhD, Robert told me that my view of being locked in an office was wrong. There would be project meetings, conferences and collaboration. For the first two years, this was certainly true. I worked together with Dutch partners on the Joint Industry Project: Autonomous Shipping and with European partners on the NOVIMAR project. I was invited to sail on the MV Endurance to perform a field study and went to several conferences across Europe. The second half of my 4 years were much more like I expected, due to the global situation. Nevertheless I very much enjoyed doing my PhD and will look back on it fondly.

The first person I would like to thank for making this possible is Robert. First of all for asking me to consider doing a PhD and after that for being my promotor. Thank you for the support, freedom and guidance you have given me over the last four year. Additionally I would like to thank Austin for being my co-promotor and providing an additional view on what I was researching. You also taught me a lot about how to play the academic *game*.

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Carmen, Leeuwarden, November 2021

A

APPENDIX A

The table underneath shows the full task database as it is used in this dissertation. The values in the table represent the conventional situation.

A

	Task properties				Relevant travel phase		
Task	Split possible	Number of crew involved	Total time in hours	Simultaneous	Loading and unloading	Arrival and departure	Normal sailing
Have responsibility for the ship during L&U	0	1	0	1	1	0	0
Have responsibility for the ship during A&D	0	1	0	1	0	1	0
Have responsibility for the ship during NS	0	1	0	1	0	0	1
Have responsibility for the engine room during L&U	0	1	0	1	1	0	0
Have responsibility for the engine room during A&D	0	1	0	1	0	1	0
Have responsibility for the engine room during NS	0	1	0	1	0	0	1
Port watch: Cargo supervision	1	1	24	0	1	0	0
Port watch: access control	1	1	24	0	1	0	0
Perform administrative duties: Loading and unloading	1	1	8	0	1	0	0
Perform administrative duties: Normal sailing	0	1	3	0	0	0	1
Work planning during L&U	0	4	1	1	1	0	0
Work planning during NS	0	4	1	1	0	0	1
Prepare food and drink during L&U	0	1	4	0	1	0	0
Prepare food and drink during NS	0	1	4	0	0	0	1
Lashing and securing of cargo during loading and unloading	1	1	0	0	1	0	0
Supervise bunkering of fuel	0	2	5	0	1	0	0
Disposal of oil waste	0	2	1	0	1	0	0
Bunkering lube oil	0	2	1	0	1	0	0
Maintenance in engine room during loading & unloading	1	1	6	0	1	0	0
Maintenance in engine room during normal sailing	1	1	7	0	0	0	1
Maintenance paperwork during loading & unloading	0	1	3	0	1	0	0
Maintenance paperwork during normal sailing	0	1	2	0	0	0	1
Watch keeping on the bridge during arrival and departure	0	1	1	0	0	1	0
Watch keeping on the bridge during normal sailing	1	3	8	1	0	0	1

	Task properties				Relevant travel phase		
Task	Split possible	Number of crew involved	Total time in hours	Simultaneous	Loading and unloading	Arrival and departure	Normal sailing
Additional watch keeping at night during normal sailing	1	1	12	0	0	0	1
Prepare bridge for arrival and departure	0	1	1	0	0	1	0
Prepare engine room for arrival and departure	0	1	1	0	0	1	0
Manoeuvring the ship during arrival and departure	0	1	1	0	0	1	0
Night watch in engine room during normal sailing	0	1	0	0	0	0	1
Watch in engine room during arrival and departure	0	1	1	0	0	1	0
Prepare deck for arrival and departure	0	4	1	0	0	1	0
Supervise deck preparation for arrival and departure	0	3	1	0	0	1	0
Handling mooring lines	0	4	0	0	0	1	0
Clean up deck after arrival and departure	0	4	1	0	0	1	0
Perform maintenance and repair of emergency equipment	0	1	1	0	0	0	1
Check Reefers (2x daily)	0	2	1	0	0	0	1
Perform maintenance of superstructure and hull	1	1	23	0	0	0	1
Maintain hatch covers	0	1	1	0	0	0	1
Perform cargo conditioning (re-lashing of containers)	1	1	24	0	0	0	1
Provide medical care and maintain medical equipment	0	1	1	0	0	0	1
Repair in Engine room during normal sailing	1	1	10	0	0	0	1

B

Appendix B

This appendix shows the complete crew capability database for the reference ship. The *1* means a crew member has the skill to perform the task, the *0* means that the crew member does not. The skills of the crew members provide a significant part of the constraints for the CAA.

	Captain	Chief engineer	First officer	1nd Engineer	1nd officer	Bosun	Cook	Able Bodied Seaman	Ordinary Seaman	Deck boy
Have responsibility for the ship during L&U	1	0	0	0	0	0	0	0	0	0
Have responsibility for the ship during A&D	1	0	0	0	0	0	0	0	0	0
Have responsibility for the ship during NS	1	0	0	0	0	0	0	0	0	0
Have responsibility for the engine room during L&U	0	1	0	0	0	0	0	0	0	0
Have responsibility for the engine room during A&D	0	1	0	0	0	0	0	0	0	0
Have responsibility for the engine room during NS	0	1	0	0	0	0	0	0	0	0
Port watch: Cargo supervision	1	0	1	0	1	0	0	0	0	0
Port watch: access control	0	0	0	0	0	1	0	1	0	0
Perform administrative duties: Loading and unloading	1	0	0	0	0	0	0	0	0	0
Perform administrative duties: Normal sailing	1	0	0	0	0	0	0	0	0	0
Work planning during L&U	1	1	1	0	0	1	0	0	0	0
Work planning during NS	1	1	1	0	0	1	0	0	0	0
Prepare food and drink during L&U	0	0	0	0	0	0	1	0	0	0
Prepare food and drink during NS	0	0	0	0	0	0	1	0	0	0
Lashing and securing of cargo during loading and unloading	0	0	0	0	0	1	0	1	0	0
Supervise bunkering of fuel	0	1	0	1	0	0	0	0	0	0
Disposal of oil waste	0	1	0	1	0	0	0	0	0	0
Maintenance in engine room during normal sailing	0	1	0	1	0	0	0	0	0	0
Maintenance paperwork during normal sailing	0	1	0	0	0	0	0	0	0	0
Watch keeping on the bridge during arrival and departure	1	0	1	0	1	0	0	0	0	0
Maintenance paperwork during loading & unloading	0	1	0	0	0	0	0	0	0	0
Bunkering lube oil	0	1	0	1	0	0	0	0	0	0
Maintenance in engine room during loading & unloading	0	1	0	1	0	0	0	0	0	0

	Captain	Chief engineer	First officer	1nd Engineer	1nd officer	Bosun	Cook	Able Bodied Seaman	Ordinary Seaman	Deck boy
Watch keeping on the bridge during normal sailing	1	0	1	0	1	0	0	0	0	0
Additional watch keeping at night during normal sailing	0	0	0	0	0	1	0	1	1	1
Prepare bridge for arrival and departure	1	0	1	0	1	0	0	0	0	0
Prepare engine room for arrival and departure	0	1	0	1	0	0	0	0	0	0
Manoeuvring the ship during arrival and departure	1	0	0	0	0	0	0	0	0	0
Night watch in engine room during normal sailing	0	1	0	1	0	0	0	0	0	0
Watch in engine room during arrival and departure	0	1	0	1	0	0	0	0	0	0
Prepare deck for arrival and departure	0	0	0	0	0	0	0	0	0	0
Supervise deck preparation for arrival and departure	1	0	1	0	1	1	0	0	0	0
Handling mooring lines	0	0	0	0	0	0	0	0	0	0
Clean up deck after arrival and departure	0	0	0	0	0	0	0	0	0	0
Perform maintenance and repair of emergency equipment	1	1	1	1	1	0	0	0	0	0
Check Reefers (1x daily)	1	0	1	0	1	0	0	0	0	0
Perform maintenance of superstructure and hull	0	0	0	0	0	1	0	1	1	1
Maintain hatch covers	1	0	1	0	1	0	0	0	0	0
Perform cargo conditioning (re-lashing of containers)	0	0	0	0	0	1	0	1	1	1
Provide medical care and maintain medical equipment	1	0	1	0	0	0	0	0	0	0
Repair in engine room during normal sailing	0	1	0	1	0	0	0	0	0	0

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Curriculum Vitæ

Carmen Kooij

Carmen Kooij was born on August 15th, 1990 in Doha Qatar. She completed her secondary education in 2008 from the Praedinius Gymnasium in Groningen. After that, she went on to complete her Bachelor degree in Marine Technology at the Technical University in Delft. This was followed by a Master degree in the same field, specializing in ship design. The master was completed in 2017 with the completion of the master thesis titled: Redesigning Allseas' Lorelay. The thesis was completed at Allseas Engineering.

After obtaining her Master's degree, Carmen started working on her PhD, focusing on the economic viability of low manned ship concepts. This dissertation is the result of that research. After completing her PhD, Carmen will continue her career as a teacher-researcher at the NHL Stenden Hogeschool in Leeuwarden.

List of Publications

Journal Publications

3. **Carmen Kooij, Austin Kana & Robert Hekkenberg** (2021) *A task-based analysis of the economic viability of low-manned and unmanned cargo ship concepts*, Ocean Engineering, DOI: 10.1016/j.oceaneng.2021.110111

2. **Carmen Kooij & Robert Hekkenberg** (2021) *Identification of a task-based implementation path for unmanned autonomous ships*, Maritime Policy & Management, DOI: 10.1080/03088839.2021.1914878

1. **Carmen Kooij & Robert Hekkenberg** (2020) *effect of autonomous systems on the crew size of ships – a case study*, Maritime Policy & Management, DOI: 10.1080/03088839.2020.1805645

Conference Publications

4. **Alina Colling, Carmen Kooij & Robert Hekkenberg** (2020) *The Effects of Automating Navigation on the Economic Viability of a Short Sea Platooning* at TRA 2020: Cancelled Conference.

3. **Carmen Kooij & Robert Hekkenberg** (2019) *Towards Unmanned Cargo-Ships: The Effects of Automating Navigational Tasks on Crewing Levels* at: COMPIT 2019 - Tullamore, Ireland.

2. **Carmen Kooij, Alina Colling & Chris Benson** (2018) *When will autonomous ships arrive? A technological forecasting perspective* at: INEC 2018, Glasgow, Scotland.

1. **Carmen Kooij, Mike Loonstijn, Robert Hekkenberg & Klaas Visser** (2018) *Towards autonomous shipping: operational challenges of unmanned short sea cargo vessels*, at: International Maritime Design Conference 2018, Helsinki, Finland.