Analyzing the Economic Benefit of Fully Electric Autonomous Vessel Variants

Recommendations on Operational Conditions

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The image on the cover of this thesis is the vision of Rolls Royce on Shore-based Control Centers for Unmanned Cargo Ships, 2016

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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on 15 July, 2021 at 14:00

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Project duration:	October 6, 2020 – July 15, 2021
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This thesis is confidential and cannot be made public until 15 July 2023

Preface

This thesis on economical effects of operational conditions on electric autonomous vessels has been written as part of the Master of Science degree in Marine Technology at the Delft University of Technology.

First, I would like to thank Carmen for her contribution to this thesis. Your guidance through the process, our online brainstorm sessions and your motivational speeches have been very appreciated. Furthermore, the amount of notes and recommendations brought this thesis to a higher level. Lastly, thanks for our good conversations about sports, which also helped me through some difficult moments.

Secondly, a special thanks to Guus who provided me with interesting details and a case study. I really enjoyed our conversations about the possibilities of autonomous shipping. I'am curious about the next steps Conoship will take on the topic of autonomous shipping!

Lastly, I wish to thank Ali Haseltalab for his help on electric propulsion, Welmoed van der Velde for her help on regulation issues, Robert for his critical questions to push me in the right direction and Arnout, Casper and Karlijn for their patience and motivational speeches.

A.A. Nijdam
Delft, July 2021

Abstract

Autonomous vessels carry the potential to increase the profitability of shipping companies. It is believed that an autonomous vessel design operates more efficient compared to a manned design. In this thesis the challenges of autonomous shipping and its consequences on ship design and the operation are identified. This information is used to give a cost analysis on the autonomous variant of a manned vessel.

The results from thesis can be used by researchers and ship owners to determine whether its autonomous ship design and its operation are economically viable. This is valuable for investors to decide whether their case is favourable for autonomous shipping. The main question answered is:

> What are the operational conditions under which an autonomous battery powered vessel design is economically viable over its electric manned variant?

First, challenges related to autonomous shipping are identified. The design and operation challenges are summarized in a checklist. These challenges concern navigation, maintenance and repair, cargo handling, communication, infrastructure, regulation, liability, safety and security. The effects of these challenges on the ship design and operation are presented. The added and removed systems result in a change in weight, power and energy consumption. These factors are believed most important for the change in ship design. Overall it is concluded that there is a significant weight and power reduction for the autonomous vessel. This is favourable for the cost, but also for the operational range under which electric propulsion is favourable over diesel engines. It is namely concluded that electric propulsion systems are only favourable over diesel arrangements for small battery capacities.

The changes in ship design and its consequences result in a change in capital and operational cost. The removed crew systems and additional equipment cost are presented. Overall a decrease in both capital and operational cost is expected.

The actual size of the cost reduction is case dependent. Therefore the operational conditions which affect the economical viability most, are identified. They are identified in a case study on a dredger operating in a port. The design and capital cost factors are presented, where after it is concluded that the displacement, battery capacity, distance to shore and the vessels specific operation influence the cost benefit. Therefore they are presented as the operational conditions.

The operational conditions are tested in two case studies. It is concluded that the displacement has a relatively small effect on the total cost. The battery capacity however, does have a significant effect. The capacity decrease is largest for vessels with an original large hotel load and large battery capacity. The larger the battery decrease, the larger the decrease in cost. Furthermore, vessels that operate within the Wi-Fi zone are favourable over vessels operating further from shore because of its communication system. Finally, the vessels specific operation regarding crew and accommodation size are most significant. The operational cost decrease for manning is larger for larger crews. In addition, the cost decrease for the accommodation section and its operational benefits are significant.

For both case studies a significant cost reduction is obtained. These vessels are thus economical viable. The size of the overall reduction is dependent on the operational conditions. Overall it is concluded that the most economical benefit is obtained for a vessel sailing close to shore, with a large hotel load, which requires a high power for propulsion, which has a large and heavy accommodation and has high crewing cost.

Contents

Glossary

AI Artificial Intelligence.

AWAA The Advanced Autonomous Waterborne Applications Initiative.

CAPEX Capital Expenditures.

COLREG International Regulation for Preventing Collisions at Sea.

HFO Heavy Fuel Oil.

IMO International Maritime Organization.

JIP Joint Industry Project Autonomous Shipping.

MARPOL International Convention for the Prevention of Pollution from Ships.

MAUSOM A Business Process Framework and Operations Map for Maritime Autonomous and Unmanned Shipping.

MUNIN Maritime Unmanned Navigation through Intelligence in Networks.

OPEX Operational Expenditures.

SCC Shore Control Center.

SFOC Specific Fuel Oil Consumption.

SOLAS International Convention for the Safety of Life at Sea.

STCW International Convention on the Standards of Training, Certification and Watchkeeping for Seafarers.

UNCLOS United Nations Convention on the Law of the Sea.

List of Symbols

Δ	Displacement of the manned vessel	$tonnes$
$\Delta_{autonomous}$	Displacement of the autonomous vessel	$tonnes$
$\epsilon_{battery}$	Specific energy of the battery	$kWh/tonnes$
η_{emotor}	Electric motor efficiency	-
η_{engine}	Diesel engine efficiency	-
η_p	Efficiency shaft engine and propeller	-
$\nu_{battery}$	Energy density of the battery	kWh/m^3
ρ_w	Density of the water	$tonnes/m^3$
b_{acco}	The beam of the accommodation	m
C_b	Block coefficient of the manned vessel	$-$
C_{adm}	Admiralty constant	$\frac{tonnes^{2/3}\cdot knots^3}{kW}$
$C_{aerosol}$	Cost for firefighting material	€
$C_{batteries}$	Batteries cost	€
$C_{batterydecrease}$	The decrease in cost for the reduced battery capacity	€
$C_{battery}$	Cost of the battery per kWh	€
C_{cables}	Cost for cables in accommodation	€
$C_{e-motor}$	Cost of the electric motor	€
C_{energy}	Energy cost for charging the batteries	€
C_{engine}	Cost of the diesel engine	€
$C_{freshwater}$	Cost for freshwater and sanitary systems in accommodation	€
C_{fuel}	Fuel cost	€
C_{HVAC}	Cost for HVAC system in accommodation	€
$C_{joinery}$	Cost for joinery of accommodation	€
C_{st}	Cost for steel accommodation	€
$C_{windows}$	Cost for windows in accommodation	€
$d_{robotarm}$	The length of the arm of the robot arm	m
E_c	Work, stored energy	kWh
$Ec_{decrease}$	The decrease in battery capacity	kWh
GM_L	Longitudinal geometric height	m
h_{acco}	The height of the accommodation above deck	m

$H_{containers}$	Height of the containers above deck	m
$h_{sailing}$	Sailing hours during a trip	h
H_{wall}	Height of the firewall in battery room	m
I	Current	A
l_{acco}	The length of the accommodation	m
L_{wall}	Length of the firewall in battery room	m
$M_{stabilized}$	Stabilizing moment	$tonm$
$M_{trimming}$	Trimming moment	$tonm$
N_{deck}	The number of decks in the accommodation	m
P	Power	kW
P_E	Effective power to the hull	kW
P_B	Brake power	kW
P_{HVAC}	Power requirement HVAC system	kW
$P_{lightingacco}$	Power requirement lighting in accommodation	kW
$P_{required}$	Power required by energy source	kW
R	Resistance	kW
$SFOC_{engine}$	The specific fuel consumption of an engine	g/kWh
T_{new}	Draft of the autonomous vessel	m
U	Voltage	$Volt$
v_s	Ship speed	$knots$
$V_{e-motor}$	Volume of the electric motor	m^3
V_{engine}	Volume of engine	m^3
V_{fuel}	Volume of the fuel	m^3
$V_{steelfirewalls}$	Volume of the firewalls installed in battery room	m^3
W_{acco}	The weight of the accommodation	$tonnes$
$W_{additionalside}$	Weight of the additional hull section	$tonnes$
$W_{batteries}$	Weight of the batteries installed	$tonnes$
$W_{e-motor}$	Weight of electric motor	$tonnes$
W_{engine}	Weight of the engine	$tonnes$
W_{fuel}	Weight of the fuel	$tonnes$
W_{fuel}	Weight of the fuel brought	$tonnes$
$W_{joinery}$	The weight of the joinery of the accommodation	$tonnes$
$W_{payloadarm}$	The weight the robot arm is able to lift at its top	$tonnes$
$W_{robotarm}$	The weight of the installed robot arm	$tonnes$

$W_{several}$	Removed weight of lifeboats, lighting, cables, wires, windows or HVAC system	$tonnes$
$W_{steelfirewalls}$	Weight of the firewalls installed in battery room	$tonnes$
B	Beam of the manned vessel	m
g	gravitational acceleration of 9.81	m/s^2
L	Length of the manned vessel	m
s	Distance weight to CoG	m
T	Draft of the manned vessel	m
α	Trimming angle	rad

1

Introduction

“Progress is impossible without change, and those who cannot change their minds cannot change anything - George Bernard Shaw [84]”.

Over the last centuries several inventions and ideas led to progress. More and more researchers and inventors find ways to increase efficiency of systems, increase ease of use, decrease costs or reduce the environmental impact. To decrease the environmental impact, improvements are made, or new techniques are applied. In order to make transport more effective, efficient, safe and sustainable, autonomous electrical cars have made their appearance. Ethical and safety issues are still high on the agenda, however the implementation is close [32].

Over the last years, also some autonomous ship prototypes have been developed [67]. Literature mentions the potential to increase the profitability of shipping companies [69], [35], [82]. In addition to the profitability, it is believed that an increase in safety and efficiency can be achieved [35]. These are interesting reasons to consider the current developments, motivation and challenges of autonomous shipping.

The design of an autonomous vessel differs from a conventional manned variant. Researchers have studied the effects on the design for autonomous ships [27], [69] [42]. However, more research is necessary to determine their potential and economical viability.

Therefore this research focuses on the possibilities of autonomous shipping and in particular electric autonomous shipping. It is concluded that electric autonomous shipping is more reliable over diesel arrangements.

In chapter 2 the characteristics, motivation and challenges of autonomous shipping are highlighted. The chapter subsequently describes the use of electric propulsion in autonomous vessels. It is highlighted that the willingness to invest in autonomous vessels is related to the feasibility and economical viability of the vessels. With that idea in mind the following research question is presented:

> What are the **operational conditions** under which an autonomous battery powered vessel design is **economically viable** over its electric manned variant?

This research question is answered using supporting questions, which are answered in the chapter 3 to 7. In chapter 3 the operational range and performance of diesel and full electric propulsion systems are presented. In chapter 4 the design changes related to sailing autonomous are described. With this information the step towards the total ship design and operation consequences is made, as shown in chapter 5. The design and operational performance result in a change in cost. This cost analysis is presented in chapter 6. In chapter 7 two case studies are performed in order to identify the operational conditions and answer the research question.

2

Literature

Autonomous vessels have the potential to increase the operational efficiency, reduce the environmental impact and carry the potential to increase the profitability of shipping companies [69], [35], [82]. To obtain an overview of all reasons and challenges related to autonomous shipping, a literature study is performed. The results are presented in this chapter. In the first section of this chapter the motivation and challenges are discussed. The section, 2.1, finishes with an overview of all challenges summarized in a checklist. In section 2.2 the reliability of propulsion systems is discussed where after the performance of electric propulsion systems are highlighted.

With the knowledge gathered in the first two sections a knowledge gap originated. This knowledge gap resulted in the research question as in discussed section 2.3. Lastly, the objective and scope are discussed in section 2.4.

2.1. In Depth Study Autonomous Shipping

In this section the motivation and challenges related to autonomous shipping are indicated. These are used to formulate the research question as found in section 2.3.1.

2.1.1. Motivation Autonomous Shipping

To take a step towards a more sustainable and future-proof shipping industry, autonomous or unmanned vessels can contribute. Several reasons are named either for sailing with a reduced crew or completely without.

Autonomous, Unmanned or Smart Ship

Autonomous shipping, smart shipping or unmanned shipping are terms that are often used interchangeably. The terms relate to a situation where no, or reduced, crew is on board during sailing. The extent to which the ship is controlled by humans, and the extent to which a vessel is manned, is often described in levels of autonomy. Different class societies define these levels. Bureau Veritas [23], Lloyd's Register [15] and DNV-GL [35] have distinguished the levels in order to set up a manual for autonomous shipping. Distinction is made between the control by human or by system. The table set up by Bureau Veritas is given as an example in table 2.1.1.

The table shows that human can fulfill different functions in the levels of autonomy. It is made clear that conventional vessels are human operated, but can possess automated operations. To reach an unmanned situation, a facility on shore is mentioned frequently. In this case the crew is replaced by a (reduced) shore crew. Several resources describe the requirement of a Shore Control Centre (SCC), DNV-GL a so called Remote Control Centre (RCC) and Lloyd's Register mentions an off-board Control System [23], [9], [35], [63]. The extent of support from a SCC however, differs per situation.

Table 2.1.1: Bureau Veritas Levels of Autonomy [23]

Ship Category	Level of Autonomy		Manned	Method of Control	Authority to make decisions	Actions initiated by
Conventional	0	Human operated	Yes	Automated or manual operations are under human control	Human	Human
Smart	1	Human directed	Yes/No	Decision support Human makes decisions and actions	Human	Human
Autonomous	2	Human delegated	Yes/No	Human must confirm decisions	Human	System
	3	Human supervised	Yes/No	System is not expecting confirmation Human is always informed of the decisions and actions	Software	System
	4	Fully autonomous	No	System is not expecting confirmation Human is informed only in case of emergency	Software	System

In some literature the control and monitoring is entirely done by the shore crew [27], [23], [9]. In other cases the SCC is mentioned as station where shore is informed in cases of emergency. Lastly, some literature describes that the system must be designed and arranged considering the autonomy level [35], [63], [12]. In this thesis full autonomy is considered. This refers to level 4 in table 2.1.1. There is a member on shore, but it is only informed in cases of emergency.

The idea of autonomous transport is not welcomed by everyone. As published in the MUNIN research (see 2.1.1), not all 70 interested respondents have a positive attitude towards autonomous shipping [57]. In addition to the attitude, not all respondents think autonomous shipping has a positive impact on the total cost. In figure 2.1.1 the opinion of the respondents on the cost aspects and the legislation implementation attitude are shown.

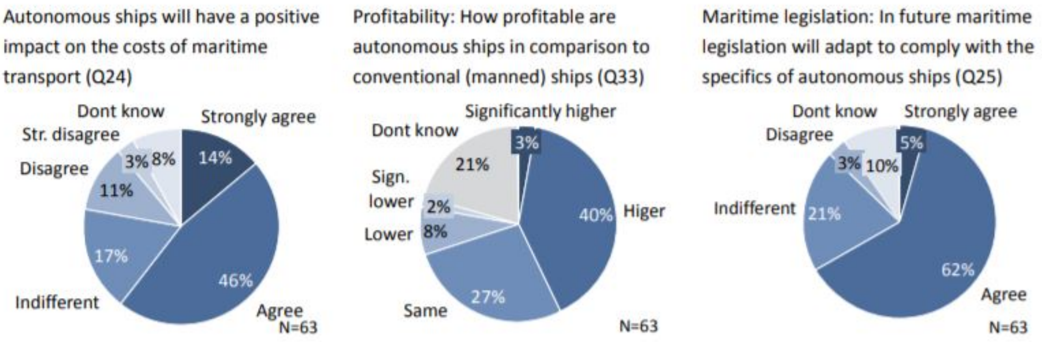


Figure 5: Respondents assessment of transport cost, profitability of shipping companies and adaptation of maritime legislation

Figure 2.1.1: MUNIN Survey Results [57]

This figure raises the question what makes the respondents look different towards the technical feasibility and cost of autonomous shipping. The knowledge of recent and ongoing projects in autonomous shipping are used to answer this question.

Recent and Ongoing Projects Focused on Autonomous Shipping

The idea of autonomous travel has existed for a long time. However, it is only for the last twenty years that projects have started to explore the options of sailing autonomous. More research is necessary to explore all possibilities, but these projects and their results represent a first big step towards realisation.

JIP Autonomous Shipping

The Dutch Joint Industry Project Autonomous Shipping (JIP), started in 2017 with an exploration and analysis of possible applications [85]. Its focus is mainly on safe navigation. This part is usually in the hands of captain and crew, the question rises how to navigate safely without or with a smaller number of crew. And additionally, if replacing the crew realises a cost reduction. The research of Kooij is part of this project [53] [54]. She identified the crew tasks during operation and the consequences of controlling from shore. These, and other research led to sea trials in 2019, held on the North Sea. The input of these trials can be used towards further realisation of safe navigation.

MUNIN

From late 2012 until 2016, The Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project focused on the potential of autonomous shipping. Several work packages started hosting several tasks. The general technical specifications of the design [103], a study on the economic situation [57] and the constraints for the new ship design [80] are made available.

In this project a case with a dry bulk carrier operating in intercontinental tramp trade is considered. It is a concept where the ship is autonomously operated by new systems on board of the vessel, but the monitoring and controlling functionalities are executed by an operator ashore, using a SCC [69]. In this project the sensor module, the navigation system, the engine and monitoring system, the shore control centre with operator and engineer are discussed. This input is used to create an overview of necessary changes and considerations.

AWAA

Another larger finished project (end of 2017) is the Advanced Autonomous Waterborne Applications Initiative (AWAA) project, led by Rolls-Royce, which aimed to produce the specification and preliminary designs for the next generation of advanced ship solutions [70]. Questions about technology, safety, rules and liability are asked in order to give a good overview of the current knowledge and possibilities of autonomous shipping. They concluded that autonomous shipping is possible from a technological perspective, but attention should be turned how people perceive autonomous shipping in the society and the industry [70].

The ReVolt

In Norway, at the University of Science and Technology (NTNU), projects involving autonomous ships are initiated. In cooperation with DNV-GL, an autonomous ship prototype dedicated for short sea shipping is designed [25], [67]. The ship, named the ReVolt, powered by a 3000 kWh battery, offers a possible solution to the growing need for transport capacity [35]. The vessel sails with 6 knots over a range of 100 nautical mile [8]. DNV-GL concludes that short shipping is favourable achieving the reliability and availability necessary for full autonomy by means of electrical propulsion.

The YARA Birkeland

Another project using the results of the MUNIN project to take the next step, is the project of the YARA Birkeland [25], [65]. It is known as the first fully electric autonomous container ship, with zero emissions. This ship is a first step towards implementation of the idea of autonomous shipping. It will be tested manned, to sail unmanned over time. The expectation is that is will be an economically viable alternative to truck transport and much more environmentally friendly. The vessel operates between three ports in Southern Norway. In 2020 the vessel was delivered by Vard Brevik. The goal is to operate autonomous by 2022 [66].

These projects prove that the autonomous shipping technologies are worth looking into. They also show that there are still several challenges to overcome. This might make respondents in the MUNIN project look different towards the technical feasibility of autonomous shipping. With respect to cost, researchers in the projects claim that autonomous shipping has the potential to decrease the cost. Some respondents still think this statement is not true. This is kept in mind when identifying the challenges.

Concluding Reasons Autonomous Ships

The projects discussed have their own motivation. Several reasons are identified for the use of autonomous vessels. The five main reasons, in no particular order, are mentioned.

1. **Reduce the environmental impact** [82],[100], [69]. A reduction in emission and fuel consumption is realised by a more efficient ship design. No crew facilities are necessary, no bridge, no ventilation systems and related systems which reduce the energy consumption. Also less life saving equipment or structures are necessary.
2. **Cost reduction** [69],[35],[82], [13]. No on board crew is left to pay. And, due to the removal of the crew, ships can stay longer at sea, lower their speed, reduce energy consumption and improve their operational efficiency. Resulting in a cost reduction.
3. **Increased safety** [35], [100], [70], [13]. With fewer people on board there will be fewer accidents involving humans. The reduction of human errors is also suggested [39]. Some literature on the other hand, states that human errors will be replaced by software errors [27], [80], [23].
4. **Reduce pressure on land-based logistics networks** [35], [82] [39]. In a world where logistics play a bigger and bigger role, autonomous vessels can contribute to reduce the pressure on land-based logistics.
5. **Solve shortage crew** [100], [69]. Finally, intelligent ships will provide owners and operators with a way to respond to the growing shortage of people who have the required maritime skills [59].

2.1.2. Challenges for Autonomous Shipping

In addition to the reasons to implement autonomous shipping, there are challenges. The idea of sailing autonomous, as far as we know, is introduced 1970's in the Rolf Schonknecht's book "Ships and Shipping of Tomorrow", [77]. The implementation is however harder that it seems. The challenges of autonomous shipping are linked to their feasibility and their economical viability. Therefore all challenges related to autonomous shipping are identified and summarized in a checklist.

For the mapping of the challenges several resources are used. Using these resources, three types of challenges are found. The first challenges are related the the absence of crew. New technologies are necessary to realise autonomous shipping. Challenges that have to do with safety and security are listed second. In the third and last section the challenges that are related to the legal implication of autonomous shipping are discussed.

New Technologies to Realise Autonomous Shipping

In a conventional ship (see table 2.1.1) most systems are controlled and monitored by the on board crew. By removing them, some of these tasks must be fulfilled by other systems or technologies. For some systems this means its functionality must be enlarged, for others new systems must be designed. In order to get an overview of all these systems, DNV-GL mapped the key function of the auto remote infrastructure . It consist of the following [35]:

- remote control and supervision
- communication
- navigation and manoeuvring
- propulsion
- steering
- electrical power supply
- control and monitoring
- watertight integrity
- fire safety
- ballasting
- drainage and bilge pumping
- anchoring
- cargo handling
- maintenance

During the design the challenge is to find the optimum way to combine these systems considering reliability, safety and cost. Most of the technologies to enable a ship to sail autonomous, in particular sensor technologies, already exist [70].

In this section the systems where most influence is exerted by the crew are explained in more detail. This is done using the list above. Ballasting, anchoring and drainage and bilge pumping are identified as ships specific tasks. The other functions are discussed in the following sections covering navigation, maintenance and repair, cargo handling, communication and infrastructure.

a. Navigation and Manoeuvring System

One of the subjects of this list is the navigation. Considering the current tasks of crew members, a significant amount of time is spend on the planning and navigation during voyage [53]. If these crew members are not available, the navigation tasks must be done autonomous. This involves not only the navigation to a certain route, but also situational awareness and collision avoidance [70], [25], [28], [83].

Lots of research is conducted to the automation of navigational tasks. In order to avoid collisions and navigate according to plan, solution are presented using the SCC or the use of Artificial Intelligence (AI) [69], [12], [19], [9]. It is believed that artificial intelligence can increase the safety when the systems become smarter and improve their visibility in comparison with humans [71]. However, by implementing AI, it is required to design algorithms that could simulate human decision making according to COLREG [32].

The navigation systems must also be suitable for the ships specific operation. The ship must keep a sufficient level of manoeuvrability and stability in various sea states, matching with the situation [23], [12].

To conclude, two challenges rise with the removal of the navigational tasks:

- Ship must be able to manage and navigate according to the voyage plan and be able to avoid collisions [69], [70], [28], [83].
- Ship must keep a sufficient level of manoeuvrability and stability in various sea states.

b. Maintenance and Repair

During a trip, a lot of maintenance is done by crew members. Without them, both human inspection and maintenance itself are gone.

In addition to the threat of not recognizing hazards, the overall safety decreases due to the lack of repairs or maintenance during operation [27], [23], [80]. This can result in major danger for the ship and its surrounding. So, a new maintenance strategy must be developed to ensure safety.

A large number of engine problems on a ship are related to fuel and combustion systems. An overview of the issues is supplied by Chae at al., who identified items to be considered for maintenance and repair as discussed above [27]. See table 2.1.2 for the identified issues and considerations.

Table 2.1.2: Identified Issues Maintenance and Repair [27]

Systems	Issues Identified	Items to Be Considered
Maintenance	• Reliable and redundant propulsion and manoeuvring systems • Wider adoption of condition monitoring system with diagnostic and prognostic functions	• Maintenance crews when a vessel is in port • Develop maintenance strategy • Integrated modules for reliability of systems
Repair	• Repair systems for errors and malfunction in software • Emergency system for firefighting, failure recovery, and repairs at sea • System to make a ship return to a port	• Resilient and redundant systems for failures • Automatic and/or remote system for repair • Cargo related problems such as cargo shift, leaks, moisture, fire and flooding

The large number of problems related to fuel and combustion systems are recognized by several researchers. Other propulsion arrangements like fuel cells, hybrid configurations or electric configurations are suggested [96], [49], [44].

Considering maintenance and repair, the following challenges must be overcome:

- Reliability of systems must be guaranteed and a suitable maintenance strategy must be developed [27], [93], [15], [98], [55].

- Monitoring and control of systems must be done adequate [69], [9].
- Systems and equipment are accessible for human inspection, maintenance and repairs [63], [23].

c. (Cargo) Handling System
During a normal trip the crew assists during sailing, loading and unloading [80], [53], [55]. In cargo vessels this implies checking the cargo condition during sailing. A system must replace the human inspection and actions in order to safely handle cargo. Dangerous cargo may not be permitted if crew is needed to safeguard it [80].

Other types of vessels must perform their ship type dependent operation autonomous. A dredger must have suitable and safe dredge systems, a passenger ship must load and unload safely. It will depend per vessel what challenges are faced.

The following challenges rise when (cargo) handling can't be done by crew:

- Cargo condition must be monitored at all times [80], [24].
- During sailing cargo condition must be ensured [24], [12].
- Ship must perform vessel specific task autonomous keeping stability and safety requirements in mind [23].

d. Communication System
Without crew the communication between shore and ship, and ship to ship, is disrupted. However, future vessels will still need this connectivity in order to give human input [70]. Communication networks using satellites are mentioned as a possibility [69], [27]. But questions remain what information to send, on what frequency and what speed. Also challenges arise how to protect this communication and how the quality is ensured. Risks, like the influence of bad weather circumstances, must be identified and discussed in order to realise a safe and suitable communication system. As Bastiaanse et al. [12] identify in their MAUSOM research, the connectivity links and prioritization of information flows under varying operational conditions must be considered. Lastly, also identified by Chae et al. [27], the third-party infrastructure, like the satellite connection, must be secured and reliable enough to work with.

Considering communication, the vessel must not only be able to send information, but also know how to receive and what to do with it:

- An autonomous, safe, secured and suitable internal and external communication system that can receive and send information must be available [27], [12], [79].

e. Infrastructure
Not only the ship design itself is considered, infrastructure on its route plays a significant role. If the ship wants to moor, or pass a bridge or lock autonomous, the infrastructure must be ready to handle it. In 'Exploring potential implications of automated inland shipping on the dutch waterway infrastructure' Van Terwisga identified the challenges that arise when sailing autonomous [94]. It can be concluded that not only the client, shipbuilder and class societies play a part, but also the administrator of the route's infrastructure.

For mooring automated mooring systems exist. At the moment several solutions are presented. MacGregor recently presented a solution where robot arms are used [65]. Other solution make use of magnets or vacuum, which replaces the lines that are normally thrown to the quay to fasten the ships. The passing of bridges, locks or dams also requires new systems and software.

Not all ports or waterways are willing to invest in an autonomous infrastructure. Solution where shore crew assist during mooring or passing bridges, dams or locks are discussed [39].

Considering the infrastructure around the sailing route of an autonomous vessel:

- The ship must posses systems in order to operate safely through bridges, docks, locks and quays [9].
- Optional: The infrastructure of locks, dams, bridges, docks and quays must be able to receive autonomous vessels [94], [9], [27].
- Ship must be able to moor/unmoor without the help of crew on board [9].

Challenge of Legal Implications

The maritime law consists of different layers and branches. National and international rules are written down in order to increase the safety on the water and limit the damage to the environment.

a. Law Framework
At first it can be concluded that the existing maritime law framework does not anticipate unmanned shipping [70]. The international rules, together with additional national regulations, do not totally cover autonomous shipping. Adjustments in the regulations are necessary. Class societies have started publishing guidelines for autonomous vessel implementation [23], [35], [63]. As researched in the MUNIN project, 79% of respondents think autonomous shipping can be realised within ten years [57]. Regulatory obstacles must be overcome within that time.

The legal implication challenge:

- Ship design and operation must meet with all relevant international and local regulations [23], [35], [81], [69], [32].

b. Liability
Liability rules may change, since new risks and new players are introduced [70]. This is dependent on the level of autonomy, and the number of autonomous operators. A collision between an autonomous versus a manned vessel may be treated different to two autonomous vessels in collision. If a ship is held responsible for a collision, or causing damage to the environment, a company, a single person, or a group of persons can be held responsible. It must be covered and written down what the liabilities are for a company, a designer and personnel.

The challenge that rises considering liability:

- There should be a clear understanding who is, at all times, responsible for the actions and failures of an autonomous ship [9],[70], [12].

c. Social Acceptance
In the automobile industry, where autonomous cars are more common, liability and safety issues are high on the agenda [45]. In autonomous shipping similar issues arise. According to the AWAA research: 'the bigger question is whether there is societal acceptance and preparedness in the maritime community and beyond to make changes to accommodate unmanned shipping' [70]. Ships sailing without crew might lead to resistance from a part of community. As discussed by MUNIN researchers, 20-30% of the respondents have a negative attitude against the impact and security of maritime transport [57]. In order to create a more positive attitude towards autonomous shipping, the community must be informed, and the risk and measures must be discussed.

The challenge that rises considering social acceptance:

- Create a positive attitude towards the implementation of autonomous shipping [70], [57].

Safety and Security Challenges

As concluded in section 2.1.1, no agreement is found by researchers considering safety of an autonomous vessel. Some researchers believe the safety increases where others highlight the new safety hazards.

a. Safety
Similar to a conventional vessel, autonomous vessels must be safe in operation, without creating threats to itself, surrounding ships or objects and the marine environment [70]. This is related to the design, type of ship, level of automation, operational area, weather conditions, maintenance strategy and more [27], [23], [15]. With the removal of the crew all visual inspections and initiatives are gone. Condition monitoring is therefore quite important, but how to react to situations using the decision support system, is even more critical. In bad weather circumstances the system can react by slowing down or change course. Even in emergency situations

the systems must be able to bring the ship to shore safely or ask for help without creating danger to traffic or the environment. These, and many more situations must be researched and implemented correctly.

On the other hand the safety increases due to the removal of crew and human errors. But, in case of a passenger ship, higher safety standards might rise since the safety of passengers must be guaranteed [23], [15].

The following challenges rise when sailing autonomous:

- A new strategy must be developed to solve: shifts of cargo, leaks, moisture, fire or flooding problems [27], [57], [32].
- In cases of (mechanical) failure, the ship must still operate safely and minimize the risk for its surroundings [103].
- A suitable and adequate monitoring technique must be applied [57]. The state of maintenance of systems must be monitored.
- Optional: In accordance with the UNCLOS, the safety of passengers must be guaranteed during sailing and (un)boarding [23], [15].

b. Security and New Hazards
The uncertainty of new hazards and risks are considered to be new challenges [70], [27]. It is undesirable that the technological development happens at quicker pace than the safety implementations. The awareness and understanding on safety and security risks to autonomous concepts must rise.

An additional challenge might rise with having the control on shore. As discussed, the SCC has the supervisory control. In the design process the critical safety hazards must be identified. Since this is a new technique, also the training of crew and back-up systems must be considered [12]. Ramos et al. [64] identified four challenges in their research: information overload, situation awareness, skill degradation, and boredom. These must be overcome and discussed during the design phase of the SCC.

Another challenge rising by implementing more systems and networks, is hijacking [32]. Piracy is already an issue with seagoing ships, but with an autonomous ship there is even less control. Not only the cargo can be stolen, but also data can be stolen or interrupted, with its possible consequences. The lack of resistance makes an autonomous vessel perhaps easier to attack [14]. On the other hand no crew can be held under shot to require money in exchange [14]. Concluding, about the extent of this threat researchers are not completely convinced, however, the systems must still be protected in case of [70]. The same applies for unlawful boarding by unauthorized persons [57].

To conclude, security is an issue for autonomous vessels. If it is proved that the vessel is at least as safe as a conventional vessel, the step towards implementation is made the smallest!

In conclusion, the challenge that rises considering security:

- The SCC must be designed keeping threats in mind and personnel must be suitable trained [12], [64].
- System is secured against hijacking or detrimental guests [35], [70], [32], [23], [25].

Discussion on the Business Case and Ethics

In addition to the challenges there are two topics to discuss. These must be included in the discussion for new autonomous vessel designs. At first the business case is discussed were after an ethical perspective on autonomous vessels is given.

Business Case
Several reasons are presented for the investment in autonomous vessels. If the cost reduction is mentioned as the motivator, the business case must be attractive. As mentioned before, not all researchers are convinced that autonomous shipping decreases the overall cost. New technologies must be developed, higher reliability and new safety measures might increase the cost. On the other hand the cost reduction is mentioned as a reason to invest in autonomous shipping. Whether the business case of an autonomous vessel is favourable over its manned variant might vary per vessel.

Ethical Issues

In this section the social acceptance of people towards autonomous shipping is exposed. Ship owners and national authorities namely have a social and ethically responsibility towards its citizen [39]. Autonomous vessels might solve the shortage in seagoing crew, but on the other hand it replaces jobs. Seafarers therefore might feel threatened by autonomous ships. There is also a possibility their activities will change. It is recommended for interests and clients to keep communicating with these crew members about the possible changes and possibilities of autonomous shipping. In addition, the safety issue is also important to include in this discussion. People might feel unsafe if vessels are sailing unmanned and might cause damage or injuries. A similar discussion is going on for autonomous vehicles, were the navigation software must decide what side to move in case of an obstacles on its path. For autonomous vehicles this is called the social dilemma, as illustrated in figure 2.1.2. The setting of the software determines who is harmed and has therefore a large impact. Discussions on possible scenario's and their impact must also be held for autonomous vessels.

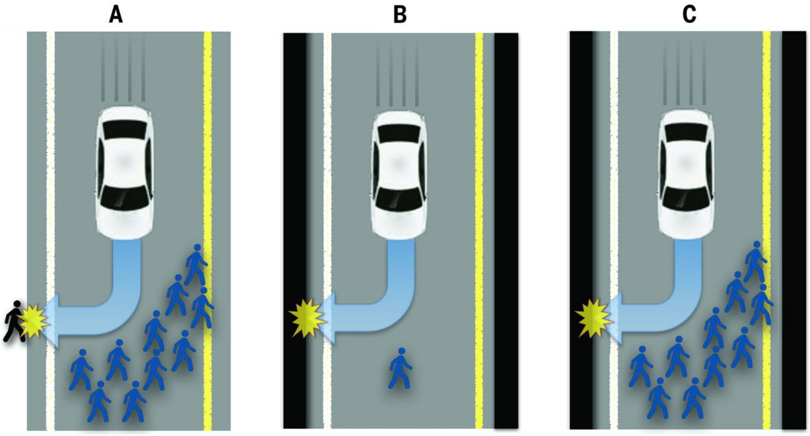


Figure 2.1.2: The Social Dilemma for autonomous vehicles [18]

Checklist Challenges Autonomous Shipping

With the challenges identified, a checklist is composed. The challenges are arranged on subject as discussed in previous section.

Table 2.1.3: Challenges Autonomous Shipping [own work]

Subject	**Challenge**
1.a.Navigational	Ship manages a pre-defined voyage plan and updates it in real-time if relevant [23]
1.a. Navigational / Safety	Ship keeps a sufficient level of manoeuvrability and stability in various sea states [23], [12]
1.a. Navigational	Ship navigates according to the predefined voyage plan and avoids collisions with obstacles coming from the traffic or unexpected objects [69], [70], [28], [83]
1.b. Maintenance and Repair	All relevant machinery and systems are accessible for maintenance and repair [63], [23]
1.b. Maintenance and Repair	Reliability level of systems is guaranteed and a suitable maintenance strategy is developed [27], [93], [15], [98], [55]
1.c. Cargo Handling	If by monitoring appears that the cargo is not correctly loaded or its condition is in bad shape ship knows how to react suitable [70]
1.c. Cargo Handling	Loading/unloading or vessel specific tasks is performed autonomous, keeping stability and safety requirements in mind [23]
1.d. Communication	Ship communicates its real-time operational data with shore [23]
1.d. Communication	A safe, secured and suitable communication system is available that sends and receives information from shore and other traffic [27], [12], [79]
1.e. Infrastructure	The ship is able to pass a lock, bridge or dock/moor safely without human help on board (or is able to manage external access) [9]
1.e. Infrastructure (optional)	The infrastructure of locks/bridges/docks on the ships route, and the home station are adjusted to be able to receive autonomous vessels [94], [9], [27]
2.a. Law Framework	Ship design and operation meet with all relevant international and local regulations [23], [35], [81], [69], [32]
2.b. Liability	There is a clear understanding who is responsible for the actions and failures of an autonomous ship [9],[70], [12]
2.c. Ethics	Autonomous shipping is socially accepted and the society is prepared to implement changes [70], [57]
3.a. Safety	The safety of passengers during (un)loading and sailing is guaranteed [23], [15]
3.a. Safety	If by monitoring, efficiency loss, cargo shifts, moisture, flood or fire is/are detected ship reacts suitable [27], [57], [32]
3.a. Safety	Condition monitoring of (weather, cargo, passenger, operational) systems and stability/strength requirements are done adequate [69], [9]
3.a. Safety	In case of (mechanical) failure, ship safely stops the operation and manoeuvres to shore safely and minimizes the risk for its surrounding (or is able to manage external access) [103], [27]
3.b. Security	System is secured against hijacking or detrimental guests [35], [70], [32], [23], [25]
3.b. Security	During the design of the SCC a high safety level is maintained and SCC is manned by trained personnel [12], [64]
4.a. Business Case	The business case of an autonomous vessel is technical and economical feasible

In this checklist the challenges related to autonomous shipping are identified. The solution to these challenges might differ per type or operation of a vessel. It is expected the solution to these challenges result in an effect on ship design [27].

2.1.3. Challenges on Total Ship Design

Some of the challenges described in the checklist have a direct or indirect effect on the overall ship design. These changes subsequently affect the business case of the vessel. It is however still unknown what factors effects this business case the most.

For the Revolt, as described in section 2.1.1, a saving of a million USD annually is estimated [35]. This electric driven ship, is sailing with a low speed and on a specified route. This ship shows that unmanned shipping is technical feasible and can be financially attractive. In this project the diesel engine is replaced by an 3000 kWh battery. The ReVolt reduces operating cost by minimizing the number of high maintenance parts such as rotational components [8].

The Revolt carries a fully electric propulsion system. The reason for this propulsion arrangement is related to reliability. Reliability is closely related to the safety level. An unmanned vessel must behave according to the rules and avoid loss of navigation, propulsion or communication as much as possible. This is partly reached with a good maintenance strategy, but also by the choice of materials and arrangements. A higher level of safety is realised when a high level of reliability is installed.

Reliability of Systems

In the MUNIN project, where a two-stroke low speed diesel engine is considered, almost 55% of the technical failures can be traced back to the main engine and its fuel oil system [103]. With the propulsion system as most vital systems on board the reliability must be increased significant to realise a safe operation. As identified by Kooij et al. [56], the marine diesel engine does not seem to improve significantly over time. In addition to the propulsion system, to prevent complete loss of manoeuvrability, communication or navigation, these systems must also ensure a high level of reliability.

Brocken [20] identified several alternatives to diesel engines. Propulsion systems were less rotating machinery is installed, and were the need for regular maintenance is low is favourable. Solutions as fuel cells or electric propulsion are presented.

In this research the choice is made to consider full electric propulsion arrangements. As identified by Brocken [20], there are no moving parts in a battery so it is likely that the reliability is equal or better than diesel arrangements. In addition, regulations are already anticipating on the reliability of electric configurations. The presence of a second, emergency electric motor is already required. In case of a failure, a second motor can provide the required propulsion to continue a safe operation. Several other researchers state that electric propulsion is a good fit to achieve redundancy [23], [15], [44]. Electric propulsion is chosen over other alternatives since it decreases the environmental impact as well.

In a full electric propulsion system no diesel engines are available. In case of a hybrid arrangement a battery pack is installed in addition to the diesel engine to provide more flexibility and increase the reliability. In this case the diesel engine is left out and a fully battery powered vessel design is considered.

In conclusion, reliability is important for autonomous operations. It is concluded diesel engines are not a perfect fit to realise a high level of reliability in autonomous vessels. The need for inspection and maintenance decreases considerable for electric propelled vessels. This arrangement increases therefore the safety and has less impact on the environment.

The next section will focus on the use of fully electric propulsion systems and its potential applications for autonomous vessels.

2.2. Electric Propulsion

As described in section 2.1, high reliability and a decrease in environmental impact are mentioned as a motivation for the use of electric propulsion. This section has the goal to indicate all possibilities and challenges of electric propulsion to decide what the operational possibilities of autonomous electric shipping are.

2.2.1. Motivation Electric Propulsion

By 2050, the International Maritime Organization (IMO) requires a 50% reduction in total annual green house gas emissions compared to 2008 levels. This requirement is set in order to encourage further efforts to phase out these emissions completely [48].

In addition to the IMO goal, there are often requirements set for low or zero emission propulsion by the shipowner [31], [82], [8]. With fully electric driven systems, where the power is supplied by batteries, this goal is reached.

In our daily life batteries are quite common, however the battery capacity of ships isn't comparable to smaller electric devices. To get a feeling of the numbers, a clear overview of some applications supplied by MAN Energy Solutions is presented in figure 2.2.1 [5].

Battery capacities of various products and vessels

	Year	Battery capacity	Character	Project costs, approx.
Mobile phone	2019	15 Wh	High-energy, short life	50 USD
Nissan Leaf	2018	40 kWh	High-energy, medium life	20,000 USD
Battery peak shaving, Grieg Star 50,000 dwt	2015	67 kWh	High-power, long life	200,000 USD (1.5 m. NOK)
Tesla Model S100d	2013	100 kWh	High-energy, medium life	100,000 USD
MAN Lion's City E (MAN Truck & Bus)	2019	480-640 kWh	High energy, long life	
***Ampere* – first modern electric car ferry**	2015	1,000 kWh	Medium-power, long life	
***Aurora* and *Tycho Brahe* – world's largest electric vessels**	2018	4,100 kWh	Medium-power, long life	35 m. USD (300 m. SEK)

Figure 2.2.1: Battery Capacity of various products and vessels (2017)[5]

The Aurora and Tycho Brahe mentioned in this table have a battery capacity of 4100 kWh. These ships, 238 meters in length, are transporting passengers over 4 km between Helsingborg (Sweden) and Helsingör (Denmark) [91]. In 2018 they were the largest in their class. The battery capacity is however growing exponentially, the Yara Birkeland is already equipped with 7000-9000 kWh [82].

The use of batteries as propulsion is used regularly on ferries shuttling between two locations, where charging takes place during boarding and unboarding [5]. Other ship types like tugs and offshore supply vessels have been equipped with electric propulsion arrangements [31], [96].

The information by Man Energy[5], Damen's electric tug [31] and the FellowSHIP project [96] is used to indicate the reasons for electric propulsion.

The reasons mentioned for the use of electric propulsion systems are:

- The redundancy of electric propulsion arrangements is higher in comparison with diesel arrangements [15], [23], [49].
- Lower operational and maintenance costs and requirements [44], [5], [49], [15].
- The oil and air-emission is reduced [60], [49].

Considering autonomous operations, the reduced maintenance cost and the longer intervals between maintenance are favourable for autonomous vessels. This means longer distances can be sailed without the need for inspection or maintenance.

2.2.2. Challenges Battery Systems

In addition to the reasons for electric systems, several challenges are presented. The challenges often differ per battery type.

Several types of batteries are in use. Helgesen et al. [44] discuss the advantages and disadvantages of several types. At this moment the lithium-ion types are most applied in ships. They have a higher energy density compared to other types, are maintenance free, have a long life and good charging efficiencies' [49]. However, biggest disadvantage of this battery type is the fire danger. Fire danger, especially in autonomous ships with no crew to extinguish, is undesirable. Measures must be taken to either prevent or extinguish fire. In autonomous vessel this means autonomous fire extinguishing systems must be available and additional fire compartmentalized rooms might be installed. In addition to fire danger, is expected that the battery pack must be exchanged approximately halfway through the vessel's lifetime [5]. Furthermore, the purchase cost for batteries are high. The cost decrease over time, but in comparison with diesel fuels the cost are significantly higher.

A third big challenge is the limited availability of some raw materials [44]. This is most applicable for the Lithium-ion types. Considering cost, it is type dependent how it compares to conventional propulsion arrangements [44].

Lastly, the technical feasibility of battery systems is limited. This is discussed more thoroughly in the following section.

Technical Feasibility of Electric Propulsion

As mentioned, most disadvantages for the use of battery systems are type dependent. The used materials, charging characteristics and energy density differ. A challenge identified in section 2.1.2 is the technical feasibility. Energy density is often identified as an important parameter for the technical feasibility of an electric propulsion system [89], [44], [5]. Energy density is given by an amount of energy per unit volume, as shown in equation (2.1).

$$Energy\ Density\ (v) = \frac{Amount\ of\ Energy}{Unit\ Volume} = \frac{J}{m^3} = \frac{kg}{ms^2} \tag{2.1}$$

In addition to the energy density, the power rate is an important parameter to compare batteries [5]. The C-rate expresses the rate at which the battery is discharged relative to the maximum capacity [49]. It is shown in equation 2.2.

$$C-rate = \frac{Power}{Capacity} = \frac{kW}{kWh} \tag{2.2}$$

In this research technical feasibility is reached when an application is socially accepted, suitable for the operation and executable. This energy density and c-rate play here a role. A high amount of energy per volume and quick battery discharge rate improve the technical feasibility. Smil [89]: 'To have an electric ship whose batteries and motors weighed no more than the fuel (about 5,000 metric tons) and the diesel engine (about 2,000 metric tons) in today's large container vessels, we would need batteries with an energy density more than 10 times as high as today's best Li-ion units'. However, not all vessels are infeasible in terms of energy density and volume. In 'Study on Electrical Energy Storage for Ships' Helgesen et al. [44] provided an overview of the technical feasibility of electric driven ships. Man Energy provided a similar study comparing four sizes of bulk carriers, three sizes of container carriers and one large ro-ro carrier [5]. They concluded that vessels like short-sea ferries are feasible with regard to weight and volume. The stage of development of battery technology is however not far enough to be competitive with regard to cost [5].

2.2.3. Summary Electric Driven Vessels

Both the advantages and challenges of electric propulsion systems are discussed in order to determine whether this propulsion system is a good fit for autonomous vessels. With the consulted literature the following conclusions are drawn:

- The reliability of electric propulsion system is expected to be higher in comparison with diesel arrangements. This is a good fit for autonomous vessels since no maintenance or inspections can be done during sailing.

- Electric propulsion arrangements are favourable for relatively small operational ranges. In addition, small ship speeds are favourable. For autonomous vessels these constraint are applicable as well. For lower speeds the autonomous vessel can easier prevent collisions and has more time to adjust its route. A small operational range ensures a certain level of safety since the vessel has a lower impact in cases of emergency since help is quicker available.
- The cost for batteries as energy supplier are considerably higher in comparison with other fuels. However, more efficient, autonomous operations might increase the economic viability.

These reasons are also identified by the researchers involved in the projects of the Yara Birkeland and the Revolt. The vessels operate under a relatively small range and speed. Those projects show the potential of autonomous electric shipping. Furthermore, those project claim that a total cost reduction is possible.

2.3. Problem Statement

It is expected that not all electric autonomous operations are feasible and realise a cost reduction. This is likely dependent on the ship type and operation.

It is also concluded that electric propulsion is only favourable over diesel propulsion over small operational ranges with regard to volume and weight. It is expected that this range increases for autonomous vessels. The size of this increase is unknown.

Some researchers describe solutions to the challenges for autonomous operations. However, the total ship design change is still unknown.

In conclusion, it is unknown what ship design changes are necessary to build an autonomous variant of an electric manned vessel. In addition, it is unknown what factors influence the economic viability most.

2.3.1. Research Question

As described in the knowledge gap, the direct and indirect consequences of autonomous shipping on the total ship design and the economical viability are underexposed. Furthermore, the consequences on the operational performance is unknown.

This research has as goal to help clients to determine whether their autonomous vessel design is technical feasible and economic viable. It provides the autonomous variant of an electric manned vessel including the cost analysis. The following research question is answered:

> What are the **operational conditions** under which an autonomous battery powered vessel design is **economically viable** over its electric manned variant?

To prevent any misconception of this defined research question, the following two terms are separately clarified:

Operational conditions - These refer to the operational conditions as identified in chapter 7;
· The displacement · Battery capacity · Distance to shore · Vessel type and operation
Economically viable - A ship is considered economically viable if its cost over the lifetime of the vessel are equal or reduced compared to the manned variant.

Sub-Questions

The main research question is answered with the help of supporting sub-questions. The sub-questions are:

1. *What is the operational range under which electric propulsion is favourable over diesel engine driven vessels?*
   In section 2.2.3 it is concluded that battery powered vessels are feasible over small operational ranges. To obtain an overview of the weight, volume and cost of this propulsion system over the operational range, a comparison with diesel arrangements is performed. This question is answered in chapter 3.
2. *To enable the transition from a battery powered manned vessel design to a battery powered unmanned design, what systems and requirements are added/removed?*
   In chapter 4 the design changes related to the autonomous operation are discussed. The additional systems are identified using the checklist as shown in table 2.1.3. For the removed systems the research by Frijters [42] is consulted.
3. *What effect do the additional systems and design requirements have on the total ship design? How big are these effects?*
   The design changes in chapter 4 have consequences on the total ship design. A change in weight, volume and cost is expected. The design spiral by Evan's [51] is used to consider most important changes. The most important changes are discussed in chapter 5.
4. *How does autonomy change the operational performance of electric vessels?*
   Not only the ship design changes. The operational performance changes as well. The consequences of the new ship design on the operational performance are also discussed in chapter 5.
5. *What are the (operational and capital) cost that arise from removing the crew of board?*
6. *What are the (operational and capital) savings of a battery powered autonomous vessel in comparison with the manned battery powered variant?* The change in design and operation result in a change in business case. Both increases and decreases in cost are discussed. They are summarized in chapter 6.
7. *What operational conditions affect the operation of an autonomous vessel most regarding economic viability? And to what extent?*
   With the information from the design, operation and cost aspects from the first sub-questions, operational conditions are identified. They are described in 7. In the case study in this chapter the operational conditions and their effect is considered for a dredge vessel.

These questions are answered in the research using the approach described in the following section. At first the questions are framed after which the steps in this research are described.

2.4. Objective and Scope

The objective of this thesis is to provide recommendations on the operational conditions, which can be used by investors or ship owners to determine whether an autonomous variant of a vessel is worth investing in. Both the ship design changes as the cost changes are presented.

This research is considered successful when a method is developed, that is able to calculate the ship design consequences and relations of removing crew of board to the economically viability. This is done using a tool which calculates both ship design consequences and cost changes. Based on the objective this tool should be able to:

- Link the challenges (table 2.1.3) to systems/requirements
- Find the power, weight and volume effects of those systems
- Identify the size of the reductions in power, weight and volume for the autonomous vessel
- Identify the consequences on ship design due to the new and removed systems

- Calculate the capital and operational cost for both the manned and autonomous vessel
- Give the economical viability over the lifetime of a vessel

In figure 2.4.1 an overview is provided of the chapters of this research.

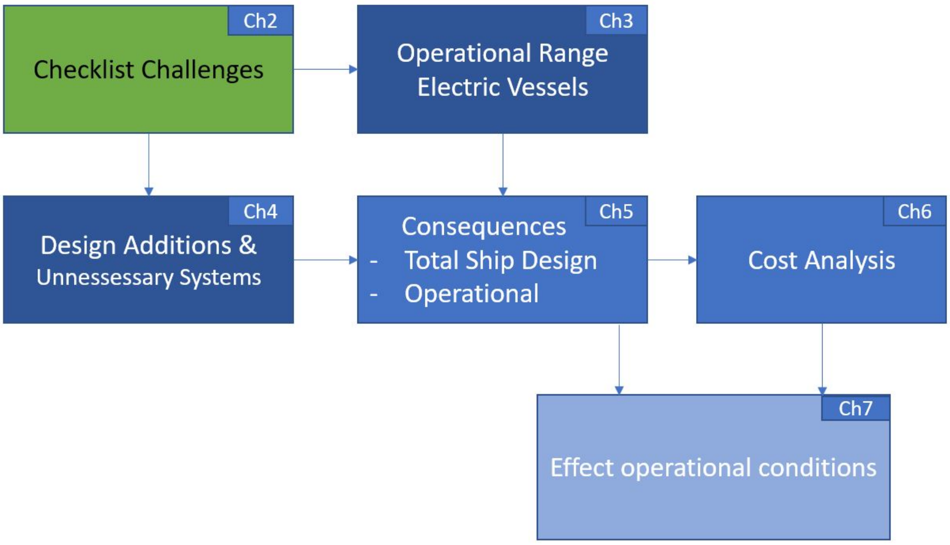


Figure 2.4.1: Research Overview

2.4.1. Scope

The proposed research question is still far-reaching. In order to narrow down the scope, some boundaries are set.

Boundary Conditions

Based on the recommendations in literature, the following assumptions are made:

- In this research level 4, full autonomy, as shown in table 2.1.1 is considered. A shore control facility is available, however no direct control is exerted. This situation is thus different than the suggested situation in the MUNIN project.
- No changes in length and width of the vessel are applied. The draft of the vessel is a variable.
- As concluded in 2.2.3, relatively small operational areas and ship speeds are considered. This also means relatively small powers are used. Larger vessels with larger installed power are not included.
- In the MUNIN [80] project it is discouraged to include cargo vessels that require frequent human inspection or carry dangerous cargo. Liquid cargo carriers like gas tankers are therefore excluded. Their technical feasibility is assumed to low.
- Only regulational barriers that affect the ship design are considered. For the implementation of the vessel it is assumed all other regulational barriers are solved.
- Ships specific tasks are not included. For example ballast, anchoring, dredging or crane handling operations are not included in the tool.

3

Operational Range Diesel and Full Electric Propulsion

This chapter covers the operational performance of electric manned vessels in comparison with manned diesel vessels. As shown in figure 3.0.1, the results of this chapter are used as input for chapter 5. The goal of this chapter is to roughly identify the characteristics of electric propulsion and the operational performance relative to diesel propulsion.

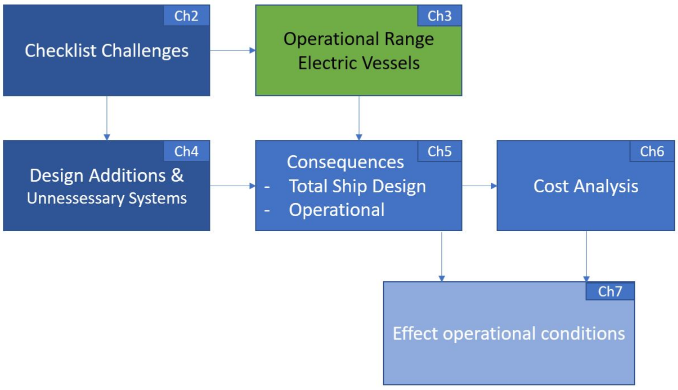


Figure 3.0.1: Overview Research

The chapter answers the first sub-question:
What is the operational range under which electric propulsion is favourable over diesel engine driven vessels?

The question is answered by looking into the characteristics of both diesel and full electric propulsion. As identified in section 2.2.2, the technical feasibility of electric vessels is related to the weight, volume and cost. Therefore a comparison on these parameters is performed. The weight of the propulsion system is important since batteries are known for their relatively high weight. A large difference in weight might lead to a change in draft and performance. The volume is more related to the dimensions, if a propulsion systems takes significant more space the ship dimensions might change. In addition, the volume of the engine determines partly how much space must be reserved in the engine room. The cost is subsequently important since ship owners strife for low expenses.

In the sections 3.1 and 3.2 respectively the characteristics of diesel and fully electric propulsion are presented. Here after section 3.3 provides an overview on weight, volume and cost of both arrangements. In section 3.4 an example study is performed. Lastly, the conclusions in section 3.5 present the answer to the sub-question.

3.1. Diesel Engine Propulsion

Diesel engines come in different shapes and sizes. For a conventional vessel an engine is selected that fits the design and power requirements. The selected engine provides this required power. The distance a vessel can sail is not only dependent on the requested power, but also of the stored energy (work). The stored energy is the power delivered multiplied by the time, expressed in kWh. For diesel engines the fuel represents the stored energy. Several fuels are used, however most vessels burn heavy fuel oil (HFO) [30]. In figure 3.1.1 a configuration is shown were single propeller is driven by a main engine. More complicated configurations, with dual engines and single shaft are also possible [86].

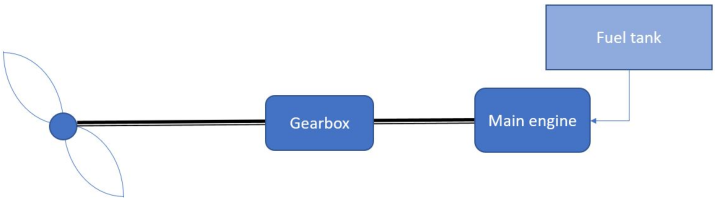


Figure 3.1.1: Single drive overview conventional configuration

To conclude, for a certain journey not only a fitting engine must be installed, also a sufficient amount of fuel must be brought. The fuel represents the work in this case. Since this fuel is burnt during sailing, the weight and volume of the fuel decrease over the maximum sailed distance.

3.2. Electric Propulsion Systems

For an electric propulsion system the energy is stored in battery packs. A battery can supply the energy needed to drive the motor. In order to drive the propeller an electric motor is necessary. IMO regulation [47] states that all electric arrangement need two electric motors since the reliability of this arrangement is not completely known. An overview of a single propeller arrangement is shown in figure 3.2.1.

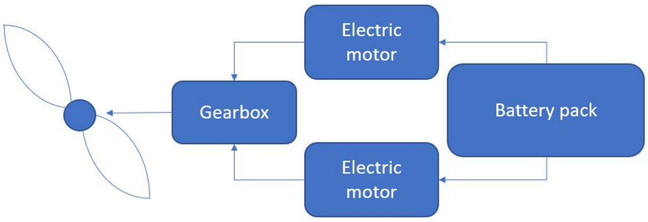


Figure 3.2.1: Single drive battery configuration

This configuration differs from the diesel engine variant. In vessel with a diesel arrangement the fuel decreases over the sailed distance. This is not the case for batteries. The batteries must be transported all journey, where the fuel is burned during sailing. In addition, as concluded in 2.1, the energy density of all batteries is significantly lower in comparison with conventional fuels. Therefore the amount of energy per m^3 is lower in an electric arrangement. So both weight and volume can cause restrictions in the operational profile of vessels. Therefore the weight and volume are considered in more detail.

3.3. Weight, Volume and Cost Both Arrangements

In this section a comparison is performed between both propulsion arrangements. It has the goal to obtain a rough sketch of the operational range under which electric propulsion is favourable in terms of weight, volume and cost.

This comparison is performed for all three parameters over the sailing distance. This sailing distance influences the size of the parameters. The parameters used in this section are shown in table 3.3.1.

Table 3.3.1: Parameters diesel used in this section

P_B	Brake power in kW	E_c	Capacity, stored energy in kWh
P_E	Engine required in kW	$P_{required}$	Power required in kW
W_{engine}	Weight of the engine in tonnes	V_{engine}	Volume of the engine in m^3
W_{fuel}	Weight of the fuel in tonnes	V_{fuel}	Volume of the fuel in m^3
η_{engine}	Efficiency diesel engine	η_{emotor}	Efficiency electric motor
SFOC	Specific Fuel Oil Consumption in g/kWh	$h_{sailing}$	Trip duration in hours
η_p	Efficiency between engine/motor and propeller		

3.3.1. Consumption

The fuel or energy consumed is dependent on the power requirements and trip duration. The consumption of both arrangements is also dependent on the total efficiency. A loss occurs by converting the stored energy towards shaft rotation and ship movement. An overview of those powers and efficiencies is given in figures 3.3.1 and 3.3.2.

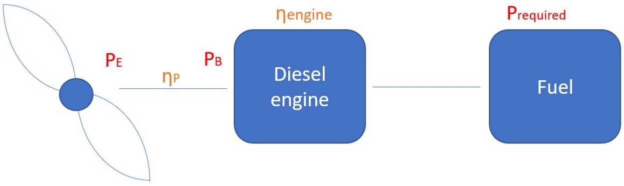


Figure 3.3.1: Powers and efficiencies diesel

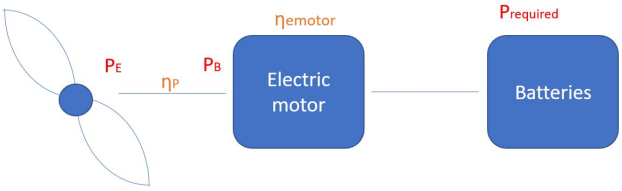


Figure 3.3.2: Powers and efficiencies electric

As shown in the figures, the consumed energy is dependent on the efficiencies. For both arrangements the required power $P_{required}$ is larger than the power supplied to the propeller. The required power expressed in terms of P_e is given in equation 3.1.

$$P_{required} = \frac{P_e}{\eta_e \cdot \eta_p} \quad [kW] \tag{3.1}$$

The total consumed energy, which is the total capacity, is given by the amount of required power by the source, multiplied by the time as shown in equation 3.2.

$$E_c = P_{required} \cdot h_{sailing} \quad [kWh] \tag{3.2}$$

3.3.2. Diesel

The propulsion weight includes the weight of the power source and components, and the fuel carried during a journey. The size of these parameters are linked to the required ship speed, installed engine and resistance. In this section a constant ship resistance is assumed to be able to perform a comparison. For a diesel arrangement some auxiliary equipment components are required. For this comparison they are not included. The weight of the engine and fuel are more significant. Since the goal is to provide a rough sketch, the auxiliary equipment is left out of the comparison.

Weight Diesel Engine and Fuel

Several examples of diesel engines and their characteristics are given by Wärtsilä [101]. Using their characteristics a rough estimation of the weight and volume per engine power is provided. A trend-line is drawn to determine a formula for the weight and volume, as shown in appendix A. With the help of these trend-lines equation 3.3 is determined.

$$W_{engine} = 0.0068 \cdot P_B + 1.5233 \quad [tonnes] \tag{3.3}$$

The fuel is also a significant part of the weight and volume that has to be included. The specific fuel consumption is dependent on the engine and its engine power. Using the engines from Wärtsilä as shown in appendix A, equation 3.4 is obtained.

$$SFOC_{engine} = -0.0044 \cdot P_B + 203.61 \quad [g/kWh] \tag{3.4}$$

The SFOC value determines the engine efficiency as shown in equation 3.5 [106].

$$\eta_{engine} = \frac{3,600,000}{40,500 \cdot SFOC_{engine}} \tag{3.5}$$

Using this equation the weight of the fuel can be calculated using equation 3.6. The total fuel is given by the consumption power over the time (E_c) and the specific fuel weight of the SFOC.

$$W_{fuel} = E_c \cdot SFOC_{engine} \cdot 10^{-6} \quad [tonnes] \tag{3.6}$$

The weight of the fuel and engine combined are referred to as the total diesel propulsion weight, as shown in equation 3.7.

$$Wtotal_{diesel} = W_{engine} + W_{fuel} \quad [tonnes] \tag{3.7}$$

Volume Engine and Fuel

For the volume of the engines also a trendline is obtained as shown in Appendix A. The volume of the engines is given in equation 3.8.

$$V_{engine} = 0.0111 \cdot P_B - 1.3029 \quad [m^3] \tag{3.8}$$

This equation gives the volume of the engine itself. However, the total volume of the engine room is significantly larger in comparison to the engine itself. The auxiliary equipment and the walkways for crew determine the dimensions. The size of the engine might vary, but is not the determining factor for the engine room size.

Therefore a comparison is performed only on fuel and battery volume. It is been kept in mind that the total volume of the diesel arrangement is conventionally larger. This comparison is however not based on exact numbers, but to provide an overview of the increase over the sailing time.

HFO is characterized by a maximum density of 1010 kg/m3 at 15°C [30]. This results in equation 3.9.

$$V_{fuel} = \frac{W_{fuel}}{1.010} \quad [m^3] \tag{3.9}$$

Cost Engine and Fuel

For a conventional propulsion system the cost are provided by Brocken [20], which is based on the theory of Aalbers [7]. Equation 3.10 shows the total engine cost in euro's. [1]

$$C_{engine} = 1322 \cdot P_B{}^{0.79} \quad [€] \tag{3.10}$$

In addition to the engine, the auxiliary equipment is a significant part of the total expenses. The cost for auxiliary equipment is approximately 25% of the engine cost [52].

Fuel cost are port and facility dependent. In addition, the fuel price fluctuates per hour and per day. Therefore a certain moment is considered, 9 March 2020. The HFO price in the Port of Rotterdam was at that moment 502.5 $\$/mt$ (C_{fuel})= 415.3 €/mt. With equation 3.4, the total cost of fuel can be calculated.

In this cost comparison the cost for the fuel tank material itself is neglected. In addition, the cost for the replacement or repairs of equipment is neglected.

The total cost as included in this comparison is given by equation 3.11. As shown in the equation the brake power, ship speed and sailing distance have a significance influence on the total cost.

$$Ctotal_{diesel} = 1.25 \cdot C_{engine} + C_{fuel} = 1.25 \cdot 1322 \cdot P_B{}^{0.79} + 415.3 \cdot E_c \cdot SFOC^{-6}_{engine} \quad [€] \tag{3.11}$$

3.3.3. Electric

In this section the parameters as shown in table 3.3.2 are used.

Table 3.3.2: Parameters electric propulsion used in this section

P	Power in kW	**U**	Voltage in Volt
I	Current in A	**R**	Resistance in kW
$W_{e-motor}$	Weight of the e-motor in tonnes	$V_{e-motor}$	Volume e-motor in m^3
$C_{e-motor}$	Cost of the e-motor in euros	C_{energy}	Energy cost in euros
$C_{batteries}$	Cost of the batteries in euros	$C_{equipment}$	Cost auxiliary equipment in euros

For the full electric arrangement an electric motor is connected to the propeller. Per propeller/thruster a separate electric motor is installed. The weight and volume characteristics of an electric arrangement can be calculated with this knowledge in mind.

For the selection of an electric motor the performance must be included. Electric motors run on a specific voltage. To reach a certain power with the given voltage, a specific current is necessary. This is shown in equation 3.12.

$$P = U \cdot I = I^2 \cdot R \quad [kW] \tag{3.12}$$

As also shown in equation 3.12, a decrease in current means a quadratic increase in resistance. A high resistance in a battery results in a lower total efficiency and shorter lifetime. Therefore a low voltage and high current is recommended to reach the asked power. Several types of electric motors are available with different characteristics [87].

Weight Electric Motors

With the help of [36] and [87], an overview of the weight, size and cost is obtained. For the motors in the range of 366 kW to 1675 kW equation 3.13 is applicable. For smaller powers the motor is typically smaller and lighter, as shown in equation 3.14. See appendix B for the figures of which the equations are based.

$$W_{e-motor_{large}} = 0.0033 \cdot P_B + 1.9473 \quad [tonnes] \tag{3.13}$$

---

[1] Since these equations were provided in USD a conversion rate is applied. The value for April 31 is applied in this thesis. On this date 1 USD was €0.83 [107]

$$W_{e-motor_{small}} = 0.0037 \cdot P_B + 0.0852 \quad [tonnes] \tag{3.14}$$

In comparison to the weight of the electric motor the battery-packs have a significant weight. For this research the Lithium-ion type is considered because of its high energy density, low maintenance, long life time and good charging efficiencies [49]. An overview of its common characteristics in energy density and power is given in figure 3.3.3. As shown in the figure, an average lithium-ion battery has a density of 100-240 Wh/kg. In comparison with an average SFOC of 190 g/kWh (5263 Wh/kg) this is a ratio of 1:52 to 1:22. The energy density of fuel is thus significantly higher.

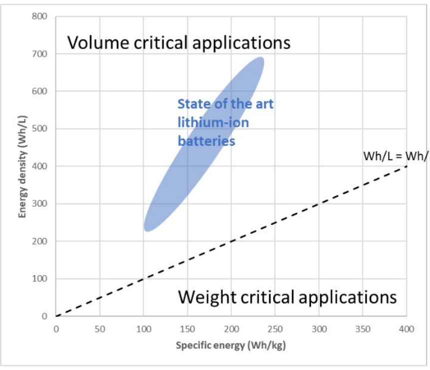


Figure 3.3.3: Lithium-ion battery characteristics [44]

Volume Electric Motors and Batteries

Corresponding to the weight equations, the volumes as found in [36] and [87] are shown in equations 3.15 and 3.16.

$$V_{e-motor_{small}} = 0.002 \cdot P_B + 0.0358 \quad [m^3] \tag{3.15}$$

$$V_{e-motor_{large}} = 0.0014 \cdot P_B + 1.6074 \quad [m^3] \tag{3.16}$$

In comparison with the diesel engine the electric motor is significantly smaller. For a brake power of 1 MW the electric motor is 3 m^3 and the diesel engine 9.8 m^3. However, as concluded the engine room dimensions are more important to include since the remaining equipment takes up a significant amount of space. The size of the fuel in contrast to the battery volume will be compared. The engine and motor size will be neglected in this comparison, but it is kept in mind that the engine room of a diesel engine is significantly larger.

As shown in figure 3.3.3, the volume of Lithium batteries are typically within the range of 240-690 Wh/L. This is equal to 240-690 kWh/m^3 [44].

Cost Electric Motor

The cost for the smaller electric motors is found by [36] and shown in equation 3.17.

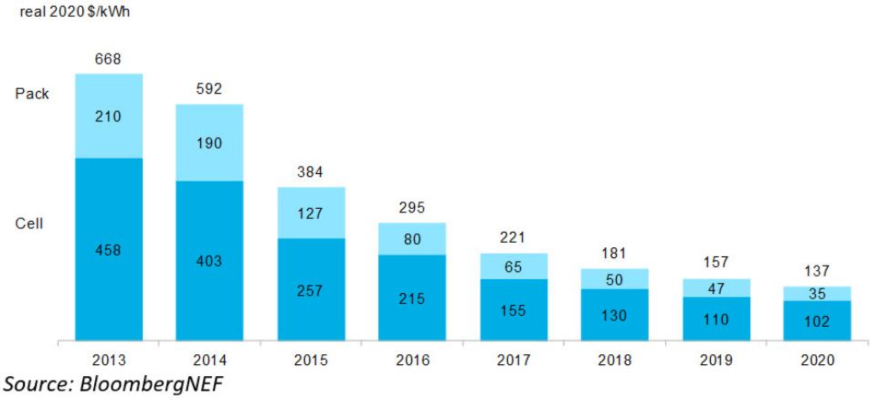
$$C_{e-motor_{small}} = 30.21 \cdot P_B + 643 \quad [€] \tag{3.17}$$

The cost for larger electric motors are difficult to predict since they are not used on big scale. In the thesis of Francis [41], the cost for electric motors is given as shown in equation 3.18. This equation is applicable for motors larger than 500 kW brake power.

$$C_{e-motor_{large}} = 100 \cdot P_B \quad [€] \tag{3.18}$$

The cost for auxiliary equipment ($C_{equipment}$), like power conversion systems or storage systems is estimated to be 250 €/kWh [41].

The cost of batteries is type dependent. For the Lithium-ion type the prices are estimated by Bloomberg [17]. As shown in figure 3.3.4 these prices also decrease over the years. For this rate the battery price in 2021 will be 110 \$ per kWh and 55 \$ per kWh in 2050!



Source: BloombergNEF

Figure 3.3.4: Cost decrease Lithium-ion batteries over years [17]

In addition to the battery itself, the charging brings energy expenses. Varying energy rates are found, from 0.05 to 0.17 euro/kWh [37], [1], [72]. These cost depend on the supplier, but also on the charging speed. Therefore a range of cost is considered. In the cost analysis it becomes clear this energy price is quite significant, therefore the correct price per case must be chosen. The cost for energy is now given by equation 3.19.

$$C_{energy} = [0.05; 0.17] \cdot E_c \quad [€] \tag{3.19}$$

The total cost for a small engine in 2020 is now given by the motor and equipment, batteries and the cost for the energy as shown in equation 3.20.

$$Ctotal_{el} = C_{e-motor} + C_{batteries} + C_{energy} + C_{equipment} = 30.21 \cdot P_B + 643 + (113 + 250 + [0.05; 0.17]) \cdot E_c \quad [€] \tag{3.20}$$

3.4. Lady Anna- Example Study

To get a feeling what parameters have the most effect on the feasibility and favourability of propulsion arrangements, an example study is presented. A sea-river vessel called 'the Lady Anna' is used for this example study. The vessel is chosen since it is suitable for both diesel and electric propulsion. What arrangement is favourable in terms of cost, volume and weight is presented in this section. The calculation neglects the weight of the auxiliary equipment. For the volume comparison only the volume of the batteries and fuel are taken into consideration. This study is performed to indicate the parameters that influence the operational performance most. The study is not performed to obtain exact numbers, but to get a rough idea.

In this example 1 propeller and 1 engine are installed to provide the required power. This means the electric variant has two electric motors and 1 propeller.

The characteristics of the vessel are shown in table 3.4.1.

Table 3.4.1: Parameters Lady Anna

v_s (knts)	ρ (ton/m^3)	Δ (ton)	P_b (kW)	SFOC (g/kWH)	η_p (-)
10	1.0	4445	749	200.3	0.55

Efficiencies

The total efficiency for the diesel and electric configuration are different. The total η_p is constant, but the engine efficiency differs.

The total engine efficiency is $\frac{3{,}600{,}000}{40{,}500 \cdot 200.3} = 0.44$. The efficiency of the electric motor is 0.85. This results in a different battery capacity as shown in equations 3.21 and 3.22.

$$Ec_{diesel} = \frac{P_E \cdot h_{sailing}}{0.55 \cdot 0.44} \quad [kWh] \tag{3.21}$$

$$Ec_{electric} = \frac{P_E \cdot h_{sailing}}{0.55 \cdot 0.85} \quad [kWh] \tag{3.22}$$

Weight

With the help of the equation 3.3 to 3.15, the total weight both arrangements are obtained. The results are shown in 3.23 and 3.24. In this equation a specific battery weight of 220 tonnes/kWh is applied.

$$\begin{aligned} Wdiesel_{total} &= W_{engine} + W_{fuel} \\ &= 0.0068 \cdot P_B + 1.5233 + Ec_{diesel} \cdot SFOC_{engine} \cdot 10^{-6} \quad [tonnes] \end{aligned} \tag{3.23}$$

$$\begin{aligned} Welectric_{total} &= 2 \cdot W_{e-motor} + W_{batteries} \\ &= 2 \cdot (0.0033 \cdot P_B + 1.9473) + \frac{Ec_{electric}}{220} \quad [tonnes] \end{aligned} \tag{3.24}$$

With these equations the arrangements are compared over sailing distance. The results are obtained using Matlab of which the codes are shown in Appendix C. Figure 3.4.1 shows that the weight for the electric propulsion increases significantly more over time. The weight of the double electric motor is approximately equal to the weight of the diesel engine, but the batteries are significantly heavier over time. If the vessel performs an operation of 10 hours, the propulsion system is 46-9= 37 tonnes heavier.

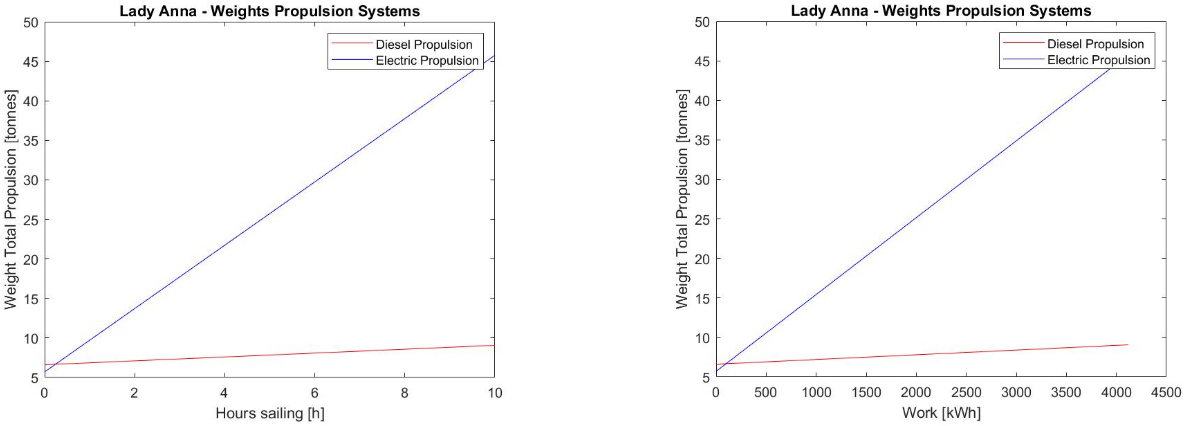


Figure 3.4.1: Lady Anna - Weight comparison propulsion system in hours and work

Volume

The batteries are increasing significantly more over sailing distance compared to fuel. It is therefore expected that the volume of batteries is also significantly more increasing over time.

The volume of the batteries is given by the capacity E_c and the density. For this comparison three different energy densities in the range of Lithium-Ion batteries are applied. Figure 3.4.2 confirms the expectation, the batteries take up more space over larger sailing distances compared to diesel arrangements.

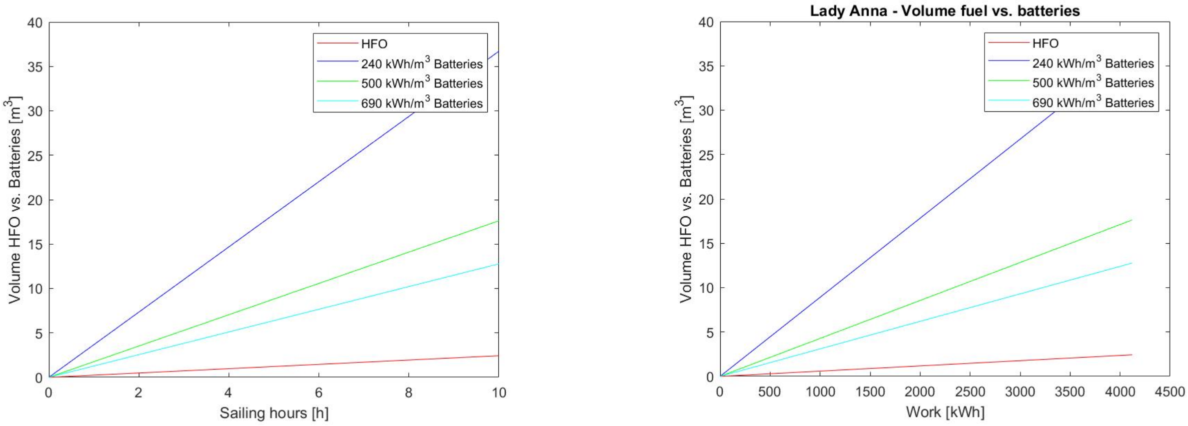


Figure 3.4.2: Lady Anna - Volume comparison fuel and batteries

It is visible in the figure that for longer sailing distances the space the batteries take in compared to fuel is larger. For large distances this might cause a problem if the same ship dimensions are applied.

Cost

For the cost also a comparison is performed. In figure 3.4.3 it is shown that the cost for the diesel engine and equipment is originally larger, but the battery price increases significant over the distance.

As shown in the figure, the decrease in battery price enlarges the area under which electric propulsion is economical viable over diesel propulsion.

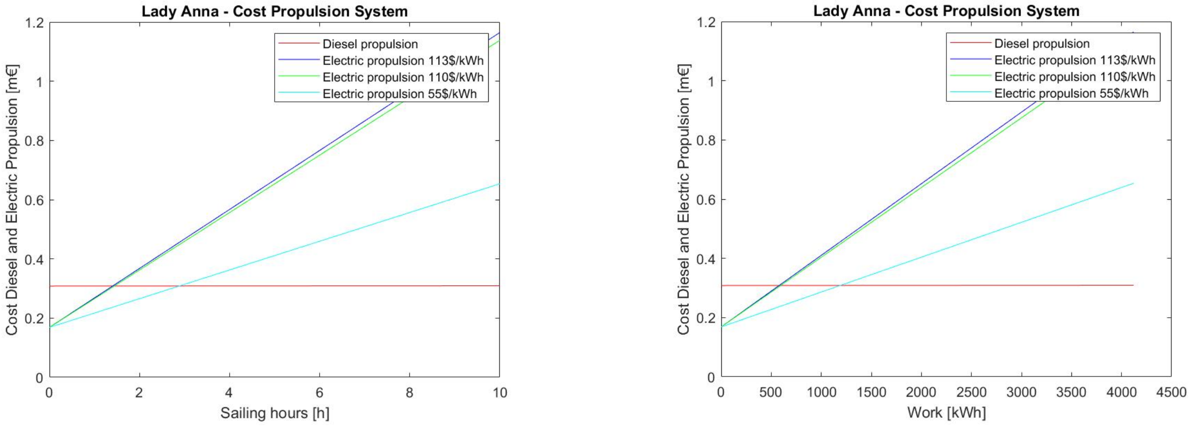


Figure 3.4.3: Lady Anna - Cost comparison diesel and electric propulsion

3.4.1. Ship Speed and Brake Power

With this example study it is shown that the range under which electric propulsion is favourable over diesel propulsion is very limited. This is concluded based on cost, volume and weight. In this section the effects are considered for a different brake power or ship speed.

It is concluded that the battery price, weight and volume increase significantly over the sailing distance. For smaller speeds, the required power is lower and the total battery capacity is also lower. Therefore the situation is considered were the vessel is sailing on 8 or 4 knots during the trip. The installed power is the same, but for the lower ship speeds, the consumption is lower. This decreases the required battery capacity (kWh). The results for both speeds is shown in figure 3.4.4. For this comparison it must be kept in mind that the distance the ship travels, decreases for lower ship speeds.

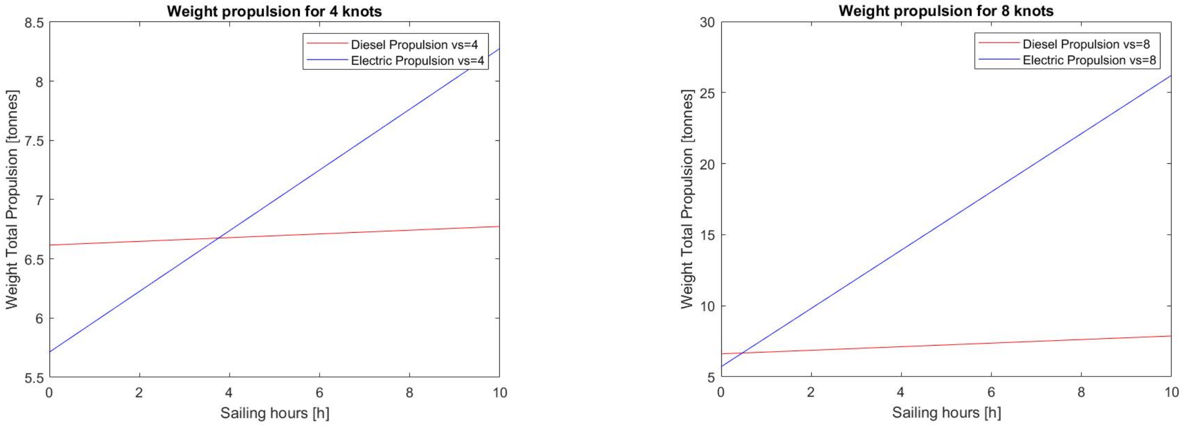


Figure 3.4.4: Lady Anna - Weight comparison for different ship speeds

It is shown that for lower ship speeds, which means lower fuel/battery capacity, the intersection point is located on a larger number of sailing hours. In the end, the capacity, the power multiplied with the time, is the limited factor for electric propulsion. For larger capacities the weight, volume and cost of the batteries increases significantly more compared to HFO.

3.5. Conclusion

In this chapter the characteristics of both diesel and full electric propulsion are identified.

With the information in this section, sub-question 1 is answered:
What is the operational range under which electric propulsion is favourable over diesel engine driven vessels?

In the first two sections of this chapter both diesel and full electric arrangements are considered. It is concluded that the weight, volume and cost have most influence on the technical feasibility and favourability of electric propulsion. In the third section a closer look into the weight, volume and cost of both arrangement is taken. It is concluded that these are dependent on the engine and the brought energy, expressed in fuel or batteries.

In the case study in the fourth section it is shown that both weight, volume and cost are a limitation for the favourability of electric propulsion. For the Lady Anna electric propulsion is heavier above capacities of 80 kWh. For this vessel that capacity is reached within an hour of sailing. Furthermore, the volume is dependent on the size of the engine room, but the size of the batteries is increasing with a factor 1.3 to 3.7 $\cdot h_{sailing}$, where the HFO increases with 0.24 $\cdot h_{sailing}$. Over 10 hours this results in a difference of 10 to 34 m^3 difference. For the cost the intersection point is located between 1.5 and 3 hours sailing, dependent on the battery price.

It is vessel and operation dependent where the turning point of favourable propulsion is located. There are however several parameters that have most influence. It is concluded that ship speed and the cost and energy density of batteries have a significance influence on this turning point location.

In conclusion, despite some rough assumptions, it is made clear that electric propulsion is not favourable over diesel for most cases. Low ship speeds (low power requirements) and small operational ranges are recommended for electric vessels. This means relatively small battery capacities are recommended. In addition, the vessel must be able to charge when on shore. Some examples of vessels that fit these requirements:

- Ferries
- Cruise ships sailing from port to port over small distances
- Small cargo ships sailing small distances
- Tankers sailing small distances
- Dredgers or work vessels
- Fishing vessels

These vessels sail on relatively easy waters with low speeds. Since their operational range is small, battery propulsion might be a good fit. The question is however, whether this operational range enlarges for autonomous electric vessels.

For autonomous vessels it is expected that the energy consumption and weight decreases. This might lead to a more efficient operation. To determine the change in operational profile at first a closer look into the ship design is taken. This change in ship design namely affects the performance change for the operation. Chapter 4 gives an overview of these design changes.

4

Design Changes Autonomous Vessel

This chapter focuses on the design changes due to full autonomy. In chapter 3 it is assumed that autonomous shipping increases the operational performance of the vessel. To be able to consider the operational performance of an autonomous vessel, the ship design changes must be known first. The goal of this chapter is therefore to identify all necessary design changes between a manned and autonomous vessel.

This chapter addresses sub question 2:
To enable the transition from a battery powered manned vessel design to a battery powered unmanned design, what systems and requirements are added/removed?

In this chapter the design changes are identified, where after chapter 5 presents the consequences on total ship design. The additional systems and requirements determine both the changes on ship design as the operational performance as shown in figure 4.0.1.

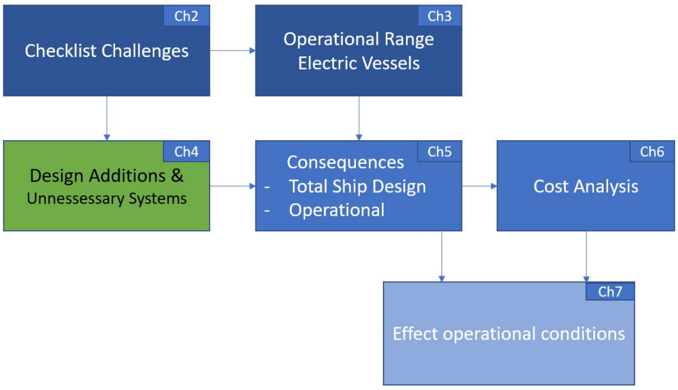


Figure 4.0.1: Overview Research

The additional systems are identified using the checklist in section 2.1. Solutions for all challenges are presented. Table 4.0.1 shows the structure of the challenges and their solutions. The design changes found are described in the order of the checklist.

The challenges identified regarding infrastructure, liability and ethics are not discussed in more detail in this section. The challenges have influence on the process, but do not influence the ship design. Therefore they are left out of the scope.

Table 4.0.1: Overview challenges identified in chapter 2

Discussed in	**Challenge**	**Solution presented in**
2.1.2 New technologies a.	Navigational	section 4.1
2.1.2 New technologies b.	Maintenance and Repair	section 4.2
2.1.2 New technologies c.	Cargo Handling	section 4.3
2.1.2 New technologies d.	Communication	section 4.4
2.1.2 Legal Implications a.	Law Framework	section 4.5
2.1.2 Safety and Security a.	Safety	section 4.6
2.1.2 Safety and Security b.	Security	section 4.6

The first six sections present solutions to the problems as shown in table 4.0.1. Section 4.7 presents several solutions to ship type dependent problems. In section 4.8 the removals related to autonomous shipping are presented. These are based on the thesis of Frijters [42], of which a summary on power and weight is presented. Finally, an answer to the sub-question is presented is provided in section 4.9.

4.1. Navigation System

The navigation system encompasses the equipment that is available to conduct navigation, record voyage data and assist in situational awareness. The challenges related to navigation and discussed in this section are shown in table 4.1.1.

Table 4.1.1: Challenges from checklist navigation and communication

Subject	**Challenge**
1.a. Navigational	Ship manages a pre-defined voyage plan and updates it in real-time if relevant
1.a. Navigational / Safety	Ship keeps a sufficient level of manoeuvrability and stability in various sea states
1.a. Navigational	Ship navigates according to the predefined voyage plan and avoids collisions with obstacles coming from the traffic or unexpected objects

To make the step towards full autonomy some of these systems need extra functions to work without human intervention. Therefore the navigation system is considered using the functional decomposition of Bastiaansen et al. [12], the systems described by Sato and Ishi [83] and the information of the MUNIN project [21]. The study resulted in the following functions:

External information:
Build and predict maritime picture. Recognize the sea states, weather circumstances and surrounding events.

Location awareness and track keeping:
Define itineraries, keep mapped track, perceive external information about the situation and avoid collisions.

Information to other vessels:
Recognize position, course, size and speed other vessels.

Internal Communication:
Provide manoeuvrability, buoyancy, stability awareness and feedback from the active systems.

The functions as described must be fulfilled by systems. Most of the systems that are necessary to perform these tasks are already available. For example the navigation trough GPS receivers or the use of radar to detect obstacles is already available on a conventional manned vessel. In the MUNIN project is is concluded that is is possible to realize a proper lookout with today's sensor technologies [25]. Table 4.1.2 gives an overview of the proposed equipment to perform the tasks above.

Table 4.1.2: Functional requirements and proposed sensor technique [own work based on [76], [79]]

Functional Requirement	Proposed Equipment
Perceive external information environment	Visual/Thermal Cameras, LiDAR, Radar, Sonar
Location awareness and track keeping	Compass, GNSS, IMU/RMU, ECDIS
Information to other vessels	AIS, VHF Radio, Sound Sensors
Internal communication & the vessels state	Machinery Sensors, Environmental Sensors, Bridge system [79]

In appendix D an overview of the proposed equipment with their related goal is given. The equipment as described in table 4.1.2 is already on the market and used in most designs. What remains is the cooperation between these systems and their tasks. No new systems need to be designed, but the systems must be able to work without a direct human intervention. The SCC can be part of the cooperation between the systems. In the MUNIN project an overview of the challenges related to this cooperation is discussed [21]. This research however focuses on the new systems, therefore no in depth study is done on this part.

4.1.1. Autonomous Mooring/Unmooring: Layout, Power, Energy Consumption and Weight

Another change in ship design is related to mooring and unmooring. To perform these tasks, an autonomous mooring system is recommended. Several solutions are presented using both on shore and on board systems and equipment [74], [65]. These solutions make use of magnets, vacuum suction or robot arms.

The use of magnets is investigated by the Port of Rotterdam [74]. This however requires an adjustment to the quay. A solution were only an adjustment to the vessel is necessary is favourable. For this research, the system used in the Yara Birkeland is considered [65]. It requires two robotic arms (front and aft) to lift the mooring line towards the bollards and fasten it. In this solution no big adjustments are necessary for the quay since the bollards are already available. Therefore the cost are only for the design of the vessel and the operational area is larger since more quays can be called.

Figure 4.1.1: McGregor mooring system used in the Yara Birkeland [65]

The arms must combine mechanics, electronics, sensors and assignments in order to operate according to the situation.

It is assumed winches and ropes are already available in a conventional design. So only the robotic arms are an extra investment.

The arms are installed on bow and stern of the vessel. If the arms are only installed on one side the vessel can moor on 1 side. It is not always possible to choose the mooring side, therefore four arms are recommended. The weight and cost of the arm is dependent on the length and payload. The payload of the arm is dependent on the length of the rope. The rope is the only load that need to be lifted, the winches regulate the tension. Steel wires are recommended because their stiffness ease the operation of fastening the rope to the bollard. This is illustrated in figure 4.1.1. These steel wires weigh 0.53 ton/100 m for a rope diameter of 36 mm. The weight the arm has to lift is now given by the reach of the robotarm ($d_{robotarm}$) in meters and the weight of the rope as shown in equation 4.1.

$$W_{payloadarm} = 0.0053 \cdot d_{robotarm} \quad [tonnes] \tag{4.1}$$

For the Yara Birkeland a reach of 21 meters must be reached. This means $21 \cdot 0.0053 = 0.11$ tonnes of ropes must be handled. In addition the arms must have a certain impact resistance. An average payload for vessels similar to the Yara Birkeland is assumed to be 0.15 tonnes. An example of an robot arm with a payload of 0.15 tonnes is given by AA Robotics [78]. This robot has only a reach of 3 meters. Larger applications are unfortunately not found, therefore an estimated for its weight is done. The weight of the AA robotics arm is 1.3 tonnes. It is assumed that 0.8 tonnes is related to the base and counterweight of the robot. The remaining 0.5 tonnes is related to the arm of 3 meters, which is 0.17 tonnes per meter. (as shown in equation 4.2) For an arm of 21 meters $0.8 + 0.17 \cdot 21 = 4.37$ tonnes of steel is used. For a ship carrying four arms, an weight of 17.48 tonnes is added to the deck. For the Yara Birkeland this is equal to 5% of the ships weight.

$$W_{robotarm} = 0.8 + 0.17 \cdot d_{robotarm} \quad [tonnes] \tag{4.2}$$

The energy consumption of the arms is mostly dependent on the movements and accelerations. For small arms a power of 2.5 kW is assumed [6], for larger arms this will increase. The energy consumption depends on the mooring time. If a mooring time of 15 minutes is applied, it will be $4 \cdot 2.5kW \cdot (0.25[h] + 0.25[h]) = 5kWh$ to unmoor and moor.

Since the arms will be installed on the deck, no changes in layout are described.

4.2. Maintenance and Repair

Maintenance and repair is also identified as an important challenge for autonomous vessels [98]. The challenges as identified in chapter 2 are shown in table 2.1.2.

Table 4.2.1: Checklist - Challenges maintenance and repair

Subject	Challenge
1.b. Maintenance and Repair	Ship is accessible for crew to perform all relevant maintenance and repair to machinery and systems
1.b. Maintenance and Repair	Reliability level of systems is guaranteed and a suitable maintenance strategy is developed

From these requirements it follows the layout of the vessels is important, and the reliability must be guaranteed. For the layout of the vessel no changes are necessary since the conventional ship design already is designed with the accessibility of crew in mind.

In section 2.1.3 it is identified that the reliability in the navigation, propulsion and communication system require the most additions to the ship design. The additions related navigation and communication are discussed in respectively sections 4.1 and 4.4. The reliability of the propulsion itself is discussed in this section. The identified passenger requirement is subsequently covered in section 4.7.

4.2.1. Reliability Electric Propulsion

In accordance with the IMO regulation [47], electric driven ships have a strict reliability in the electric motors and propulsion. For this research it is assumed that an electric vessel has a reliable electric motor structure, generators and converters. This means a double electric motor is already installed to provide a back-up system in cases of emergency. However, for an autonomous vessel, reliability is even more important. As recommended by an expert, the possibility is considered to the split battery packs in more parts. This ensures a certain percentage of propulsion left in case of a failure in the batteries itself. In addition, it is possible to choose different operating profiles or operations. And, it can help with the ship design and increases the flexibility in a lot of cases.

Dividing the batteries leads to a small change in both weight, volume and efficiency of the batteries.

4.2.2. Maintenance and Repair: Layout, Power, Energy Consumption, Weight

The division of the batteries potentially leads a decrease in electrical losses. This is supported by equations. In equation 3.12 ($P = U \cdot I$) the total power is shown, where in equation 4.3 the losses are shown. The total power is subsequently given by equation 4.4.

$$P_{loss} = I^2 \cdot R \quad [kW] \tag{4.3}$$

$$P_{total} = P - P_{loss} = U \cdot I - I^2 \cdot R \quad [kW] \tag{4.4}$$

For smaller batteries the resistance (R) might be lower, which causes a smaller loss. On the other hand, more distribution losses might occur due to more difficult arrangements. It is highly arrangement and lithium-ion type dependent what the exact benefits or drawbacks are. In this case the batteries are distributed to increase the reliability. In case a higher efficiency is realised, a smaller installed power is necessary. The same goes for a lower total efficiency, in that case more installed power is necessary. Since it increases or decreases the size of the installed engines this effects the weight and volume as well.

The division of the batteries results in an increase in volume and weight as well. To increase the safety in the battery rooms, fire resistance walls are added. These rooms are often called fire compartmentalized rooms [44]. Regulation states that a minimum of A-0 level bulkheads must be installed. The additional weight due to additional steel is dependent on the battery room surface. The thickness of the steel, 4 mm, and the stiffeners every 6 meters represent the added weight [26]. A specific steel density of 7.8 kg/dm^3 is used. With these numbers an estimation of $0.04 \cdot m^2$ tonnes is added for the battery room. Equation 4.5 shows this addition for the length and height of the wall.

$$W_{steelfirewalls} = 0.04 \cdot L_{wall} \cdot H_{wall} \quad [tonnes] \tag{4.5}$$

For example, a battery pack of 5000 kWh and corresponding engine room of 10 m^3 this results in an weight addition of 3.3 tonnes.

The volume addition related to the distribution of these battery packs is given by the volume of walls and some additional space. The result is dependent on the added battery weight as shown in equation 4.6.

$$V_{steelfirewalls} = \frac{1.02 \cdot W_{steelfirewalls}}{7.8} \quad [m^3] \tag{4.6}$$

For the distributed battery pack of 5000 kWh this results in an volume addition of 0.44 m^3 (104%).

4.3. Cargo Handling and Vessel Specific Tasks

Two challenges emerge from cargo handling as shown in table 4.3.1. This section consist of two parts, vessels that carry cargo, or vessels with an other specific operation.

Table 4.3.1: Checklist - Challenges cargo handling

Subject	Challenge
1.c. Cargo Handling	If by monitoring appears that the cargo is not correctly loaded or its condition is in bad shape ship knows how to react suitable
1.c. Cargo Handling	Loading/unloading or vessel specific tasks is performed autonomous, keeping stability and safety requirements in mind

4.3.1. Cargo Ships

The tasks done by crew for inspection and cargo handling must be replaced by autonomous systems [24]. The tasks related to inspection and handling of the cargo are given below.

Cargo Monitoring:
This includes monitoring of: temperature, status, movements, fumigation, generation of gasses, oxygen depletion [16]

Cargo Securing:
Cargo securing is important during loading and unloading, but also during sailing. The hatches must open and close to control temperature and gasses. The cargo must be secured well against movements [23].

The systems identified above are available in conventional ships, but controlled by human. This control in an autonomous vessel can either be done using the SCC or automated systems. For monitoring this means advanced monitoring systems must be available. Automatic alarms and temperature monitoring is available in conventional vessels to assist the crew [16]. The cargo securing however, is more difficult to find a fitting solution for. Most solutions presented require additional security for the cargo. For example the Revolt uses separate cargo holds to prevent containers to shift [8]. This requirement has therefore effect on the structure and layout.

4.3.2. Cargo Handling: Layout, Power, Energy Consumption, Weight

Cargo ships that have separate cargo holds and an extended hull to prevent containers to shift have effect on the layout and weight.

The extended hull might have consequences for the number of containers as well. As shown in figure 4.3.1, the containers above deck must be rearranged in the situation the sides are extended.

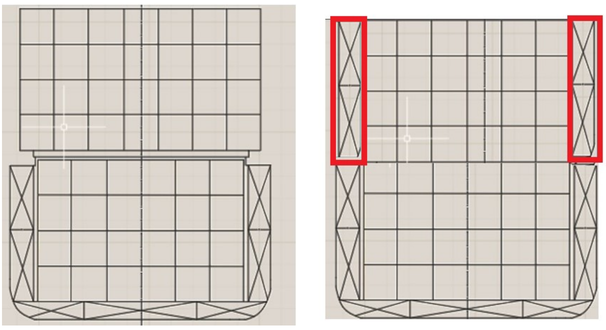


Figure 4.3.1: Conventional cargo structure and new arrangement. In red the additional side structure is highlighted. Based on [88]

Assuming a single side and a thickness of 7+0.04 · L mm [61] and a steel weight of 7.8 tonnes/m^3 the equation as shown in 4.7 is obtained. In this equation $H_{containers}$ is the height of the steel to cover the containers above deck.

$$W_{additionalside} = 7.8 \cdot (7 + 0.04 \cdot L) \cdot 10^{-3} \cdot L \cdot H_{containers} \quad [tonnes] \tag{4.7}$$

For a vessel of 60 meters and three additional container layers of 7.77 meters, this results in an added weight of 34 tonnes. This added weight might result in an increase of the ships draft, dependent on the significance of the addition. This consequence is discussed in more detail in chapter 5. The addition of the holds does not have a direct effect on the power or energy consumption.

4.3.3. Non Cargo Ships

For non cargo ships, like dredgers, passenger vessels or offshore vessels, other vessel specific tasks must be performed autonomous. For example, for vessel carrying a crane doing dredge operations, systems must be available to ensure a safe operation. For crane operations alarm situations and ballast systems must be available. Since this is vessels specific, no further conclusions are drawn here.

4.4. Communication System

In this section the challenges as shown in table 4.4.1 related to communication are discussed.

During a conventional voyage several communication between shore and ship, or ship to ship, occurs. There is also communication within the ship itself. This is called internal and external communication.With the

Table 4.4.1: Challenges from checklist navigation and communication

Subject	Challenge
1.d. Communication	Ship communicates its real-time operational data with shore
1.d. Communication	A safe, secured and suitable communication system is available that sends and receives information from shore and other traffic

help of the checklist in section 2.1.2, several sub requirements are identified using Bastiaansen et al. [12] and Chae et al. [27]:

External: Data communication with shore

The shore control center must know the status of the ship and report to authorities. Also alarm shore in cases of emergency.

External: Data communication to other traffic

The ship must feature a system that can communicate with other ships. The ship must feature a system that can prioritize information flows. These systems must work under all operational and weather conditions.

Internal Communication

The ship must detect the status of the systems on board: Detect failures and alarms, determine buoyancy and stability and estimate the manoeuvrability.

In the MUNIN deliverable d4 [79] issues about the security and reliability of communication systems and services are discussed. The MUNIN researchers conclude that some services are not suitable for the use in autonomous vessels.

At first it must be made clear that a trade-off between reliability and cost must be made. For ships sailing close to shore, maybe the use of a WiFi connection or 3/4G can be realised, where ships sailing further from shore use satellite connections [79]. Therefore this section is split up in two parts, ships sailing within 20 km from shore, or ships sailing further from shore.

4.4.1. Applications within Radio Range

The ship to ship information can be stored and send using a digital VHF (Very High Frequency) or using the AIS. As identified in the MUNIN project is the use of these systems is vulnerable to security attacks [79]. On the other hand, in cases of emergency also help is quicker provided since the distance to shore is close. An additional communication systems therefore seems superfluous and not worth the extra investment.

An overview of the most relevant communication systems based on the information by MUNIN is shown in table 4.4.2.

Table 4.4.2: Most relevant communication systems [79]

System	Type	Usage Area	Protocols and capacity
Ship to ship	LOS	Ship rendezvous	AIS, digital VHF radio
Ship to shore	LOS	Ship control and monitoring during coastal approach	3G-4G; WiFi; WiMAX; TCP/IP and UDP

LOS:line of site;

In this table AIS and a digital VHF radio are already available on a conventional vessel. A Wi-Fi connection however, is not. Most conventional vessels make use of a satellite communication, to provide internet on board and enable the crew to use their telephone or send messages to shore [34]. When the crucial information can be send using Wi-Fi and no crew is on board that need to make calls, this satellite connection is unnecessary. Wi-Fi could be developed by the client and protected. The use of 3G or 4G will also be good alternatives to satellite communication, but might cause problems with frequencies [79]. A cheap and good secured Wi-Fi connection for vessels sailing within its reach is therefore chosen as the best fit.

Wi-Fi connectors must be installed to realise the connection. For the installation of a good Wi-Fi connection, receivers are installed. Several providers sell those receivers and accessory products. An example is the Wave WiFi system [104] which makes uses an antenna and a receiver. Its reach is up to 7 miles. The corresponding power requirement is 0.8 kW and its weight is negligible small.

4.4.2. Applications further from Shore

When sailing outside the radio range, the use of satellite connections is recommended. But also the reliability issue is of bigger importance. Therefore the MUNIN projects recommends the use of two independent communication systems. It is favourable to use systems working on different frequency bands. In the MUNIN project Iridium and VSAT are suggested solutions [79]. An iridium system is working on a frequency of 1 to 2 gHz were VSAT is working on a 4 to 8 Ghz. However, VSAT is normally a quite expensive service. Working on both frequency bands increases the reliability.

It must be noted here that some satellite services have a lower degree of availability in certain areas of the globe [79]. These areas are however not in the scope of this research and therefore not an obstacle.

An overview of these systems is shown in table 4.4.3.

Table 4.4.3: Most relevant communication systems [79]

System	Type	Usage Area	Protocols and capacity
Ship to ship	LOS	Ship rendezvous	AIS; Digital VHF Radio
Main ship to shore via satellite	SatCom	Ship control and monitoring at high seas	VSAT systems; TCP/IP and UDP
Backup ship to shore via satellite	SatCom	Backup at high seas	Iridium; TCP/IP and UDP

LOS:line of site; SatCom: communication using space satellite.

4.4.3. Communication: Layout, Power, Energy Consumption and Weight

Several of the systems described are already available in a conventional vessel. However the use of them and the knowledge about failures, the reliability and the security issues must be discussed in more detail. But overall it can be concluded that for a vessel sailing within 20 km from the radio station the use of 3/4G or WiFi must be made available. And for a vessel with a bigger range two frequency systems must be installed to ensure a reliable communication.

The energy consumption an Iridium system is small, 3.5 W [2]. Over a trip of several hours this is negligible. The VSAT connection has more influence on the installed power and energy consumption. A maximum of 0.55 kW power is required for this connection [38].

The weight and layout changes due to these additions are negligible small.

4.5. Additions due to Regulations

In this section the design change due to regulation are discussed. The regulations that might effect the ship design are included. These effects come forward from the challenge as shown in table 4.5.1.

Table 4.5.1: Checklist - Challenge regulation

Subject	Challenge
2.a. Law Framework	Ship design and operation meet with all relevant international and local regulations

The challenge in table 4.5.1 represents all national and international regulations. As also identified in section 2.4.1, the international rules that have a direct effect on the design of the vessel are included in this research. Therefore the rules of the COLREG, SOLAS and Loadline Convention are considered. The regulations of the MARPOL, UNCLOS and STCW are left out of the scope. In the MARPOL regulations are drawn up in order to protect the marine environment. An autonomous vessel might lead to less garbage or sewage, but overall no design changes are necessary to fulfill the requirements. Therefore no further attention is paid to this regulation. In the UNCLOS it is stated what is understood with international waters or territorial waters. This regulation is therefore quite significant, however a direct effect on the design of the autonomous vessel is not found. The STCW covers all standards on training, certification and watch-keeping for seafarers. This regulation must be adjusted to shore crew, but has no direct effect on the ship design.

4.5.1. COLREG

The COLREG, describing the regulations for preventing collisions at sea, is applicable for all ships upon the high seas and connected waters therewith navigably by seagoing vessels [75]. The regulations do not fully anticipate autonomous vessels. Therefore, the regulations that have biggest effect on the ship design are investigated into. The three rules are shown in table 4.5.2.

Table 4.5.2: COLREG rules that need closer look

COLREG	Rule	Ship design additions
COLREG - Rule 5	Proper look-out obligation	Equipment that can replace human eyes and ears and subsequently act accordingly to the situation
COLREG - Rule 8	Operational/avoidance decissions	Situational awareness and avoidance making equipment
COLREG	Communication	Equipment that is able to inform other ships about its status and intentions.

COLREG rule 5 and 8: Proper look-out & Situational awareness

According to the COLREG regulation rule 5 [75]:
"Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision"
According to the COLREG regulation rule 8 [75]:
"Any action to avoid collision shall be taken in accordance with the Rules of this Part and shall, if the circumstances of the case admit, be positive, made in ample time and with due regard to the observance of good seamanship."

In an autonomous vessel the look-out must be replaced and additional situational awareness must be created. Several researchers describe the use of a sensor that is responsible for object detection and classification and environmental perception [69], [70]. Most of these systems are already available. In the project for the Yara Birkeland [44] a combination of proximity sensors is used. This includes radar, LiDAR, AIS, camera and IR camera's. These systems can replace the function of 'look-out' and thus the human eye. If this system is also able to build a local map of objects and potential hazards the functions situational awareness and collision avoidance are included as well. To comply with the COLREG it is concluded that additional redundancy is necessary to ensure proper lookout and situational awareness at all times.

Additional Redundancy Autonomous Vessel
The systems mentioned above are all on the market and frequently used in conventional vessels. In addition to the research the working mechanism between these sensors, additional reliability is necessary. This means that in cases of failure the situational awareness detection must still be realised. Some of the systems must therefore be duplicated to ensure the reliability.

Table 4.5.3: Systems situational awareness and their failure cases

System with failure	Lost function	Partly solved by
GPS	Position autonomous vessel	Compass, SCC
LiDAR	Distance to own vessel and exact size of obstacle	Radar
Radar	Long distance detection objects, all conditions	LiDAR
AIS	Position and characteristics traffic in surrounding	GNSS, Camera's, Lidar, Radar, SCC
Camera's	Maritime picture	Radar, Lidar
ECDIS	Sea Route determination	AIS, SCC

In case of a failure in one of the systems the functioning can completely or partly solved by an other system. From a small reliability study (see table 4.5.3) it is concluded that both the maritime picture and the awareness is crucial.

With that conclusion it is recommended to install both an additional radar and daylight/infrared camera.

This is done to ensure the detection on obstacles both on short and long range. In addition a sound receiver to sense objects and warning events is recommended [76], [35].

4.5.2. COLREG: Layout, Power, Energy Consumption and Weight

Additional Radar An additional radar is installed to ensure the situational awareness. If one of the radars fails an extra option is available. There are two frequencies available, the 3 GHz s-band is used for a sharp and high resolution image, where the 10 GHz x-band is used in rain or fog. Both radars are therefore doubled in order to ensure the situational awareness at all times. The weight of the radars is negligible small. The power of the receivers however, is estimated to be 10 kW for the x-band, and 25 kW for the s-band up-mast receiver [29]. This relates to an energy consumption of $0.05\ \mu s \cdot 1760 Hz = 0.32 \cdot [10-25] kW$ per hour.

Camera's

As concluded, an additional daylight/infrared camera is necessary. A combination of daylight and infrared camera, used for detection of traffic and obstacles is shown in figure 4.5.1. An average combination camera used by Flir [40] has an nominal energy consumption of 4.8 W and 12.5 W max.

When the accommodation of a vessel is removed (see 5), the camera's range decreases since it is installed lower on the ship. It is therefore recommended to put the original and the added camera on places such that all sides of the vessel are covered. These camera's do contribute to the energy consumption and weight. These additions are however negligible and therefore left out of the calculations.

Figure 4.5.1: Daylight Camera [102]

Sound Receivers

In addition an array of several sound receivers are required [76]. It is estimated that they are needed on starboard and port side midships, and on the aft and front. An overall power of 1 kW is assumed [90], which energy consumption relates thus to $1\ kW \cdot h_{sailing}$. Their weight is negligible.

The overall effect of the additions as described is shown in table 4.5.4.

Table 4.5.4: Additional Sensors

System	**Weight**	**Layout**	**Max Power Requirement**
x-band radar	negligible	front	10 kW *
s-band radar	negligible	front	25 kW *
Daylight and infrared Camera	negligible	front/aft	0.0125
Sound receivers	negligible	front, aft, SB, PS	1 kW
Additional for navigation system	negligible	-	**1.0125 kW**

* These systems only require power in case of emergency, it has therefore no effect on the peak power

4.5.3. SOLAS

For constructional requirements the SOLAS describes the requirements. This regulation is applicable for all cargo, passenger and tanker ships. The operational area is not of influence.

Table 4.5.6: SOLAS rules that need closer look

SOLAS	**Rule**	**Ship design additions**
SOLAS - II-1	Stability	Damage stability and watertight layout changes. Doors and openings might change of position.
SOLAS - II-2	Fire protection	Fire integrated system. Structural design change due to absence crew.
SOLAS - III	Life-saving arrangement	System to assist vessels in need. Obligatory!
SOLAS - IV	Radio communication	More extensive and safe communication system (see 4.4)

SOLAS II-1: Stability

As identified by de Vos [99], the damage stability and watertight layout of doors might change. This might change the total layout. A constant length and width are assumed in this thesis. The recommendations by de Vos could be used during the optimising phase of the vessel. Since this is not the focus of this thesis, the effect on weight, power and energy consumption is therefore zero.

SOLAS II-2: Fire Integrated System

As identified in 2.1.2, no crew is available in cases of fire. The autonomous vessel must therefore minimise the risk of fire, detect fire and be able to contain and extinguish it [63]. In a conventional vessel however, several measurements are already taken. For this research it is assumed that detectors and sprinkles are available.

With the help of the crew a fire can be extinguished and damage can be repaired. In an unmanned vessel the consequences of fire are larger. Since no repairs can be done, or no crew can respond to alarms, the risk of fire must be minimized. Therefore several solutions are presented to solve this risk:

- Additional fire protection of the battery packs. (more fire-doors/rooms)
- Automatic extinguishing systems are the best fit for autonomous vessels
- Use aerosol system (potassium based) instead of water. Since water can cause a lot of damage, systems that use very little water or no water at all are recommended [11].

Changing conventional fire extinguish equipment to aerosol systems does not significantly effect the overall weight or volume. Two significant changes are identified for the fire issue: At first the manual controlled buttons for crew must be replaced by extra detectors. The SCC crew might play here a role as well.
In addition extra safety issues regarding fire of the batteries must be taken. These have been discussed in 4.2.

SOLAS-III: Life Saving Arrangement

According to SOLAS-III a vessel is obligated to assist a vessel in need [62]. It is assumed the navigational system is capable of alarming traffic and shore about the situation. The vessel might not be capable of assisting people in need since this task is often performed by crew members.

For this regulation no addition power, energy consumption, weight or layout change is made since no additional systems are installed.

4.5.4. Loadline Convention

The loadline convention is describing the rules concerning freeboard. The possible changes due to regulation 25 are shown in table 4.5.7.

Table 4.5.7: Loadline Convention: Rule that need closer look

Loadline Convention	Rule	Ship design additions
II-Reg 25	Accommodation, freeboard and guardrails on superstructure and open decks	Accommodations removed Freeboard might be little lower. Guardrails might be removed

Ships that are loaded require a certain freeboard. With smaller freeboards a certain safety issue rises. For autonomous vessels no harm to crew can be exerted which decreases this risk. Smaller freeboards might be chosen, but on the other hand the hull must be secured against unwanted guests. An autonomous vessel does not want people to climb its hull to enter the ship. Larger freeboards decreases this risk. Therefore no change in the current freeboard is expected.

4.6. Safety & Security

The challenges that have effect on the ship design and have to do with safety and security are shown in table 4.6.1. These challenges are considered separately and discussed in this section.

Table 4.6.1: Checklist - Safety Challenges

Subject	**Challenge**
3.a. Safety	If by monitoring, efficiency loss, cargo shifts, moisture, flood or fire is/are detected ship reacts suitable
3.a. Safety	Condition monitoring of (weather, cargo, passenger, operational) systems and stability/ strength requirements are done adequate
3.a. Safety	In case of (mechanical) failure, ship safely stops the operation and manoeuvres to shore safely and minimizes the risk for its surrounding (or is able to manage external access)
3.b. Security	System is secured against hijacking or detrimental guests
3.b. Security	During the design of the SCC a high safety level is maintained and SCC is manned by trained personnel

4.6.1. Condition Monitoring and Management

The challenges in table 4.6.1 are both related to monitoring and managing. At first it is concluded that monitoring systems are necessary to detect problems like efficiency losses or water leaks. Most of these systems are already available. If not, they must be added to guarantee a quick response to those potential risks. The management of the systems is more complicated. Deliverable D4-5 of the the MUNIN project describes a first draft for the cooperation between ship and shore systems. The cost related to these software modules is described in chapter 6.

4.6.2. Safety & Security Increase

As identified the safety and security is guaranteed by a high level of reliability. For some vessels this safety level is easier guaranteed than for others. Therefore a short overview is given of circumstances that improve the safety level.

- Easy weather circumstances: Stability, navigational and manoeuvrability requirements are easier maintained.
- Low traffic density: The more vessels or obstacles on a ships route, the more complicated the software modules must be.
- For vessels sailing relatively short trips more (preventive) maintenance could be performed. This increases the safety.

No specific design additions follow from these conditions.

4.7. Specific Design Additions

Several of the requirements mentioned do not apply for all situations. The possibilities of carrying passengers or autonomous lock passing are two examples. They come forward from the challenges in table 4.7.1. Some clients will choose the possibility to hire crew to perform these tasks, others require a system. These will be discussed in this section.

The requirements are identified using classification societies and other literature. This section will discuss the possibility to carry passengers, autonomous loading/unloading and autonomous lock passing. For the passing of bridges the autonomous navigation system has the control. No systems are added for that requirement.

Table 4.7.1: Checklist - Challenges optional passengers/infrastructure

Subject	Challenge
3.a. Safety	The safety of passengers during (un)loading and sailing is guaranteed
1.e. Infrastructure	The ship is able to pass a lock, bridge or dock/moor safely without human help on board

4.7.1. Carrying of Passengers: Layout, Power, Energy Consumption and Weight

For this requirement a distinction must be made between a passenger ship and a ship carrying passengers. This requirement means the situation were not more than twelve passengers are carried. When a ship is carrying more passengers, the regulations for a passenger ship are applicable.

If passengers are brought, some extra safety concerns rise. In addition to extra safety levels, it means that life saving equipment and other equipment must be available. The safety of the passengers must be guaranteed. These safety equipment is already available in a conventional vessel, but can not removed since there are passengers on board. In addition to these removals that cannot be performed, the weight of the passengers itself is dependent on the number of passengers ($n_{passengers}$) included as shown in equation 4.8.

$$W_{passengers} = n_{passengers} \cdot 0.075 \quad [tonnes] \tag{4.8}$$

Other equipment like passenger management system must be available. In case of a man overboard, the system should provide means for alerting and rescuing [23]. It is assumed that the navigation system has such a function.

4.7.2. Autonomous Loading/Unloading: Layout, Power, Energy Consumption and Weight

Loading or unloading can either be done using crew on shore or fully autonomous without the help of crew. Autonomous loading and unloading has the potential to make the process more efficient. An optional addition for autonomous vessels is therefore an autonomous loading and unloading system. Looking at current technologies, several autonomous terminals are already available. For ports it is also favourable to invest in autonomous terminals since their leading time can be improved. For example the port of Rotterdam is anticipating autonomous ships by 2030 and wants to be able to host them by then [105]. For the Yara Birkeland a company is hired to design the equipment and technology needed for realising autonomous shipping. These equipment will mostly be on the account of ports. On the ship itself no significant changes are necessary. It is however possible to have cranes on board for loading/unloading. But if that is a requirement of the client, it is probably already available on the conventional vessel.

4.7.3. Autonomous Lock Passing: Layout, Power, Energy Consumption and Weight

Several researchers are considering the passing of locks. At this moment the regulatory barriers prevent ships from passing locks autonomous. If these barriers are overcome, autonomous lock passing might lead to quicker leading times. If the ship can communicate its status to the lock, the availability can be aligned [9].

In the Smart Shipping Hackathon the TU Delft team presented a solution using arms and rolling hooks to pass the lock [97]. It is assumed the same arms as used for autonomous mooring can be used. A similar power and weight are assumed. For the energy consumption the power must be multiplied by the (un)lock time.

4.8. Removal of Systems

Not only additions are necessary on the new ship design. Also several removals are possible. The size of the reduction differs per vessel. In the research of Frijters [42], an overview is provided of reductions to two unmanned container vessels. The equations applied by Frijters are used in this research to give an estimation of both the weight and power reduction.

4.8.1. Weight Reductions

In the research of Frijters [42], several systems and equipment is identified that contributes to the total weight of the vessel. A breakdown structure with all systems that are present to support life on-board is given. This breakdown consist of the following systems:

- Hull and outfitting (steel accommodation, windows)
- Primary ship systems (fresh water, sanitary systems, HVAC in accommodation)
- Electrical systems (cables, wires and lighting in accommodation)
- Deck equipment (lifeboats and lifesaving equipment)
- Secondary systems (firefighting equipment accommodation, joinery and hotel equipment)
- Nautical, navigation and communication equipment (internal communication, entertainment systems)

The most significant weight reduction according to Frijters [42] is the removal of the steel and joinery in the accommodation. Indirect effects like the fresh water and HVAC used in the accommodation are removed as well. Their weight contribution is however significant lower.

Removal of Steel

The accommodation of the conventional vessel is removed. Without crew no accommodation and facilities are necessary. Therefore, the complete accommodation section is removed. Frijters identified different values for the weight of sides, top, back and decks of the section [42]. With help of the parameters in table 4.8.1 the total weight reduction for the steel in the accommodation is specified as shown in equation 4.9.

Table 4.8.1: Clarification parameters

W_{acco}	The weight of the accommodation [tonnes]
b_{acco}	The beam of the accommodation [m]
h_{acco}	The height of the accommodation above deck [m]
l_{acco}	The length of the accommodation [m]
N_{deck}	The number of decks in the accommodation [m]

$$W_{acco} = 0.18 \cdot b_{acco} \cdot h_{acco} + b \cdot l \cdot (0.05 \cdot N_{deck} + 0.08) + 0.16 \cdot h_{acco} \cdot l \quad [tonnes] \tag{4.9}$$

For the Lady Anna vessel in chapter 3, the accommodation is approximately 500 m^3. When two decks are available, a reduction of approximately 35 tonnes of steel is realised. For larger accommodations this reduction becomes even larger.

Joinery of Accommodation

For the joinery of the steel in the accommodation a lot of material is used. The weight of the joinery ($W_{joinery}$) can therefore be a significant part. According to Frijters [42] it can be estimated using equation 4.10.

$$W_{joinery} = 0.15 \cdot (b_{acco} \cdot l_{acco}) \cdot N_{deck} \quad [tonnes] \tag{4.10}$$

The weight of the joinery is dependent on the number of decks, but similar in size to the weight of the steel. For the Lady Anna vessel this comes down to approximately 30 tonnes.

Other Reductions

In addition to the steel and joinery of the accommodation do other smaller systems contribute to the weight reduction. The windows, cables, wires, firefighting systems, HVAC system and wires in the accommodation are removed. Furthermore, the hotel equipment and entertainment and internal communication systems are removed. In the research of Frijters these reductions are described separately [42]. For this research an estimation of those smaller systems combined is given. These systems are dependent on the size of the accommodation. Therefore the factor between joinery and steel, and the rest of the systems is considered. With the help of the results of Frijters [42] it is estimated that approximately 25% is a suitable factor. In equation 4.11 the total weight for these other systems is given.

$$W_{several} = 0.25 \cdot (W_{joinery} + W_{acco}) \quad [tonnes] \tag{4.11}$$

It must be noted here that the research of Frijters [42] focuses on large container feeders. The vessels in this research are smaller and have a shorter operational range. Therefore a certain uncertainty is taken into account for this estimation.

4.8.2. Energy Consumption & Required Power

Not only a weight reduction is realised for autonomous vessels, the power requirement also decreases. The systems identified by Frijters [42] that require power are the HVAC system, the lighting in the accommodation, the hotel systems, internal communication and the entertainment systems.

HVAC System

The HVAC system is the largest contributor to the energy consumption in the accommodation [42]. Other consumers like the hotel equipment and entertainment systems have a significant smaller contribution.

In the research of Frijters [42] the HVAC system energy use of the accommodation is considered. It is expected that the HVAC system in the rest of the ship cannot be removed since repairs and maintenance must be possible in safe working conditions. The energy consumed by the HVAC system is dependent on the volume flow, the air changes per hour and the temperature. Frijters gives an estimation for this power requirement for both winter and summer conditions [42]. These are dependent on the volume of the accommodation (V_{acco}). The equations are shown in 4.12, 4.13.

$$P_{HVAC,winter} = 9.43 \cdot 10^{-2} \cdot V_{acco} \quad [kW] \tag{4.12}$$

$$P_{HVAC,summer} = 2.24 \cdot 10^{-2} \cdot V_{acco} \quad [kW] \tag{4.13}$$

For the accommodation of the Lady Anna of 500 m^3 this results in a power requirement of 11.2 to 47.15 kW.

Hotel Equipment

The hotel load is highly dependent on the installed equipment in the accommodation. Energy consumers like fridges or computers can namely be removed. For the vessels used by Frijters a power requirement of 15 to 50 kW is estimated [42] ($P_{hotelload}$). For vessels only sailing during days, no additional equipment like washing machines or dryers are necessary. A smaller reduction is realised when these vessels are built autonomous.

No exact numbers are given in this section. In chapter 7 a case study is performed where the hotel power requirement and energy consumption are given in detail.

Lighting, Internal Communication and Entertainment System

The lighting in the accommodation is given by the armature power and floor area (A_{floor}), as shown in equation 4.14 [42]. The $P_{Armature}$ value differs per type of lamp (50-70 W).

$$P_{lightingacco} = \frac{2.13 \cdot 10^{-1} \cdot A_{floor} \cdot P_{Armature}}{10^3} \quad [kW] \tag{4.14}$$

For the Lady Anna with a floor area of 200 m^3 2.6 kW of power is required for lighting in the accommodation.

For the internal communication system and entertainment system require power as well. However, as also identified by Frijters [42], their contribution is negligible small.

4.9. Conclusion Design Changes Autonomous Vessels

In this chapter it is concluded that an autonomous vessel design differs from conventional vessels. Both reductions and additions are applicable to the design.

The second sub-question is answered: *To enable the transition from a battery powered manned vessel design to a battery powered unmanned design, what systems and requirements are added/removed?*

The total additions and removals in weight and maximum power are shown in table 4.9.1. The energy consumption is dependent on the operation of the vessel.

Table 4.9.1: Overview weight increase/decrease

System	*Weight* [tonnes]	*Maximum Power* [kW]
Robotarms	+ 4 · $W_{robotarm}$	+ 2.5 kW
Firewalls	+ $W_{steelfirewalls}$	/
Cargo hull	+ $W_{additionalside}$	/
Communication - close to shore	negligible	+ 0.8 kW
Communication > 20 km	negligible	+ 0.55 kW
Navigation	negligible	+ (36 kW)
ICT	negligible	Case dependent
Accommodation steel & joinery	- (W_{acco} + $W_{joinery}$)	/
Several other equipment acco	- $W_{several}$	/
HVAC system	- W_{HVAC}	- $P_{HVAC,winter}$ or - $P_{HVAC,summer}$
Hotel equipment	negligible	- P_{hotel}
Lighting	negligible	- $P_{lighting}$

The additions in weight for mooring arms and additional fire protective walls become irrelevant compared to the removed weight for accommodation and equipment. The size of the accommodation has therefore a significant contribution to the change in total weight. The power requirement for the robot arms, communication system and navigation system are relatively small compared to the removed hotel load and HVAC power requirement. In conclusion, the removals in weight and power are larger compared to the additions, which results in a consequence on ship design. Therefore the consequences on total ship design and operation are covered in the following chapter.

5

Consequences Total Ship Design

This chapter describes the consequences on the ship design due to the additional and unnecessary systems. As shown in figure 5.0.1 the results from chapter 3 and 4 are used as input. The output subsequently is used as input for the cost model in chapter 6.

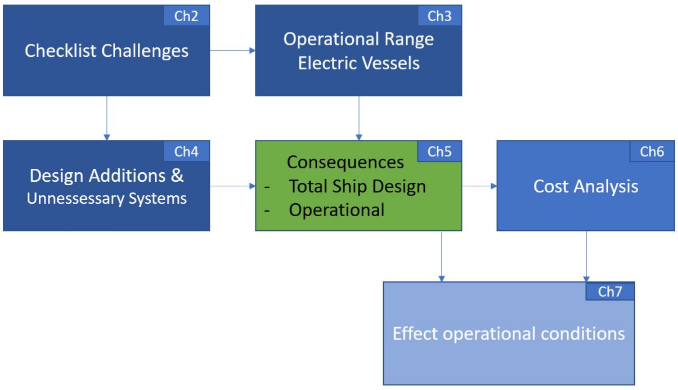


Figure 5.0.1: Overview Research

This chapter does not run through all the steps of the design spiral. In this research the consequences on ship design that have most impact on the ship design are included. As emphasized in section 2.4.1, the dimensions of the ship are assumed constant.

In the section 5.1 the changes in weight as identified in chapter 4 are discussed. Section 5.2 covers the change in displacement where after section 5.3 presents the change in trim. Section 5.4 subsequently describes the change in power and energy with the information from chapter 4 and the change in displacement from the second section. In figure 5.0.2 these steps are shown in the design spiral.

These steps answer the fourth sub-question: *What effect do the additional systems and design requirements have on the total ship design? How big are these effects?*

In section 5.5 the operational changes due to the new ship design are discussed, which answer the fifth sub-question: *How does full autonomy change the operational performance of electric vessels?* Lastly, section 5.6 provides a conclusion on the consequences on ship design and operation.

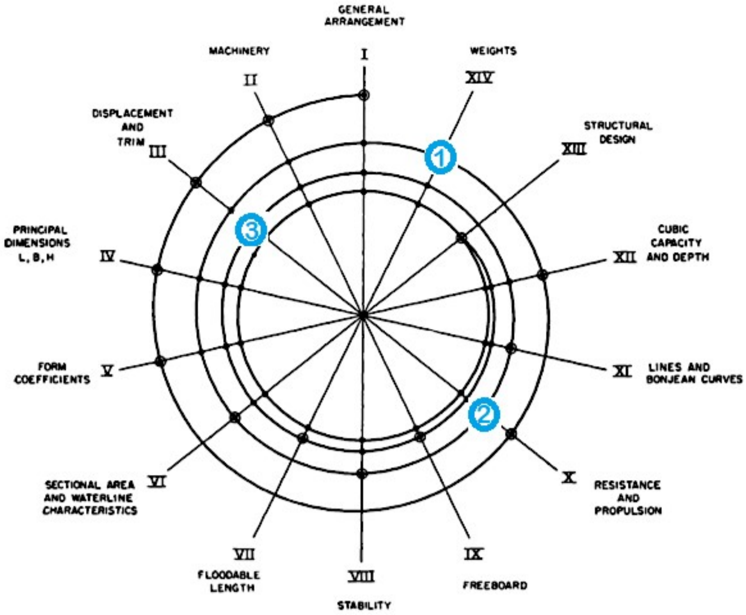


Figure 5.0.2: Steps taken into consideration [51]

5.1. Lightweight

The lightweight of a vessel represents the displacement of a ship in tonnes without cargo, fuel, lubricating oil, ballast water, fresh water, consumable stores, and passengers and crew and their effects [62]. The changes in chapter 4 results in a decrease or increase in lightweight. In table 5.1.1 an overview of systems and equipment discussed in chapter 4 is shown.

Table 5.1.1: Lightweight additions and removals vessel

Equipment	Discussed in section	**Added or Removed Weight**
Navigation - mooring	4.1	+
Additional fire wall(s)	4.2	+
Cargo handling	4.3	+ [1]
Communication/Navigation	4.4, 4.5	negligible
Safety and Security	4.6	/
Passengers	4.7	+ [2]
Locking	4.7	+ [3]
Steel/joinery accommodation	4.8	-
Lighting, cables, wires, windows, hvac removals	4.8	-

Minus (-) represents a reduction in weight, Plus (+) an increase
[1] In case of a cargo vessel; [2] In case passengers are brought; [3] In case of a lock passage

The size of the reductions and additions in table 5.1.1 determines if there is an increase or decrease in lightweight. However, it is expected the total lightweight of the vessel decreases since the removal of the accommodation is significant in comparison with other additions.

5.2. Displacement and Draft Change

The displacement of the conventional vessels is given by the volume of water that is displaced by the ship converted into weight. The typical water densities (ρ_w) vary between 0.997 and 1.025 ton/m^3. The displacement of a conventional vessel is shown in equation 5.1 [95].

$$\Delta = \rho_w \cdot L \cdot B \cdot T \cdot C_b \quad [tonnes] \tag{5.1}$$

The displacement changes due to the addition and removal of the weights as shown in table 5.1.1. A new displacement is now given by the displacement minus the change in weight (δ_W) as shown in equation 5.2.

$$\Delta_{\text{autonomous}} = \Delta + \delta W \quad [tonnes] \tag{5.2}$$

Since the dimensions of the ship are taken constant, only the draft is the variable factor. This draft changes with the change in displacement. It is given by equation 5.3.

$$T_{new} = \frac{\Delta + \delta_w}{L \cdot B \cdot C_b \cdot \rho_w} \quad [m] \tag{5.3}$$

It is expected that the change in weight (δ_w) is negative due to the size of the reductions. This means a decrease in ship draft is expected.

5.3. Trim Shift

The change in weight not only results in a new displacement, also the trim shifts. It is expected that reduced weight of the accommodation section results in forward trim. A change in trim results in a change in resistance since the waterline changes.

This section covers the consequence on trim. The removal of the weight and additions namely have effect. The position on the vessel where these reductions or additions are, is important for the total trim. For this section it is assumed the changes are most significant in longitudinal direction. This is mostly due to the removal of the deck house. The center of gravity of the accommodation section lies relatively high in comparison with the center of gravity of the hull. In the new situation the stability slightly increases since its total metacentric height will increase.

In longitudinal direction the conventional vessel has a certain trim which is dependent on the trimming and stabilizing moment [95]. The equations corresponding to those moments are shown in equation 5.4 and equation 5.5.

$$M_{stabilized} = \rho \cdot g \cdot \nabla \cdot GM_L \cdot sin(\alpha) \quad [Nm] \tag{5.4}$$

$$M_{trimming} = m \cdot g \cdot s \cdot cos(\alpha) \quad [Nm] \tag{5.5}$$

With 's' the distance from a certain mass towards the center of gravity is meant. A change in weight is most significant if it is placed far outside the center of flotation. In figure 5.3.1 this is shown for the deckhouse.

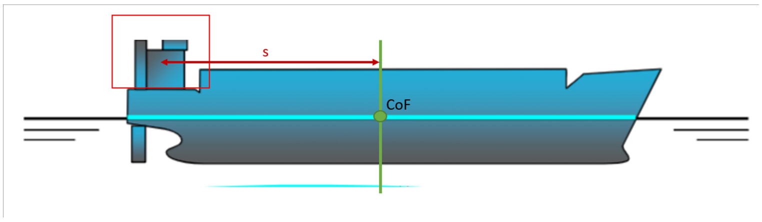


Figure 5.3.1: Moment deckhouse = s · $W_{deckhouse}$

For all removals and additions a trimming moment is obtained. The trim is subsequently found by equalizing both equations $M_{st} = M_{tr}$. The result is the trimming angle α, as shown in equation

$$\begin{aligned} M_{st} &= M_{tr} \\ \frac{sin\alpha}{cos\alpha} &= \frac{m \cdot g \cdot s}{\rho \cdot g \cdot \nabla \cdot GM_L} \\ \alpha = \tan^{-1}(\frac{m \cdot s}{\rho \cdot \nabla \cdot GM_L}) &\quad [rad] \end{aligned} \tag{5.6}$$

The total trim in meters is subsequently given by equation 5.7.

$$trim = L \cdot tan\alpha \quad [m] \tag{5.7}$$

By removing the weight of the accommodation, which is often far from the center of gravity, the vessel inclines forwards. In the optimisation step of the vessel this new trim must be considered and in some cases be adjusted by changing the ship layout.

5.4. Effect Power and Energy Consumption

In this section the effect the design changes have on the energy consumption are considered. Both power and work are discussed. These changes are both caused by the additions and removals in chapter 4 and their changes in weight and displacement.

5.4.1. Propulsion Power

In chapter 4 it is concluded that dependent on the efficiency of the division of the batteries additional or a reduced power is necessary. In addition to this change due to the division of the batteries stands the displacement change. The displacements, and in particular the draft change, results in a change in resistance. This translates subsequently to the necessary installed power to reach the conventional speed. The change in installed power is given with the Admiralty constant shown in equation 5.8 [106]. This equation is applicable since the ship dimensions are constant, only the displacement and installed power change.

$$C_{adm} = \frac{\Delta \cdot v_s^3}{P_B} \quad [\frac{tonnes^{2/3} \cdot knots^3}{kW}] \tag{5.8}$$

With the expected decrease in displacement a smaller brake power (P_B) is obtained. This is a result of a decrease in resistance. This smaller brake power requires an engine with a lower maximum power requirement and a lower energy consumption.

5.4.2. Hotel Power

In addition to the installed propulsion power there are several other energy consumers. In chapter 4 the removals arose from the removal of crew systems and the additions related to the new systems are discussed. An overview of these consumers is shown in table 5.4.1.

Table 5.4.1: Consequences on Power and Energy Consumption

Equipment	Added or Removed Power
HVAC System	-
Hotel Power	-
Navigation System	+
Communication System	±
Mooring System/Lock System	(+)

The HVAC system and hotel power have a significant effect on the total power. The systems shown in table 5.4.1 all work simultaneously. Their summation is the total power that need to be installed. For an autonomous vessel it is expected that the overall removed power is more significant in comparison with the additions. An overall decrease in power and energy are expected.

5.4.3. Energy Consumption

The change in the power requirement and the change in draft change the overall energy consumption.

Both an increase and decrease of energy consumption is realised. On the one hand the additions systems like the radars require energy to perform their tasks, but on the other hand the removed (crew) systems lower the energy request.

Furthermore, the decrease in power requirement results in a lower energy consumption. Since this engine provides a lower power for the same ship speed the overall energy consumption is decreased as well.

The total installed work, stored in battery packs, is given by the power used for propulsion, for hotel systems and for specific operations like dredging or crane handling multiplied by the time. An operational limit is set for the batteries to prevent it from being fully charged or discharged (100% to 0% state of charge). On average this results in an increase of battery capacity of 1.4. In equation 5.9 the derivation to determine the battery capacity over a certain trip is shown.

$$Ec_{total} = h_{sailing} \cdot (P_{propulsion} + P_{hotelload}) + h_{operation} \cdot P_{operation} \quad [kWh] \tag{5.9}$$

For an autonomous vessel it is expected this total capacity (Ec_{total}) decreases. The propulsion power ($P_{propulsion}$) is lower due to the decrease in draft. In addition the hotel load decrease might be larger than the additional energy for the new systems.

5.5. Consequence on the Operational Range

In this chapter it is concluded that the draft changes due to a change in added and removed weights. The change in draft results in a change in installed power. Several researchers expect a decrease in operational cost due to a more efficient operation [9], [25]. This statement is tested with the results in this chapter. The change in power and draft namely gives a different operational profile in comparison with the manned vessel. This is demonstrated with the example ship the Lady Anna from chapter 3.

It is expected that, mostly due to the weight of the removed accommodation, the displacement will decrease. Therefore three scenarios are discussed, a decrease in displacement of 5%, 10% or 15% compared to the conventional vessel is tested. With the help of the Admiralty constant in equation 5.10, a new displacement and installed power are obtained. The numbers related to the three situations are shown in table 5.5.1.

$$C_{adm} = \frac{\Delta^{\frac{2}{3}} \cdot v_s^3}{P_B} = \frac{4445^{2/3} \cdot (10 \cdot 0.5114)^3}{749} = 48.27 \quad [\frac{tonnes^{2/3} \cdot knots^3}{kW}] \tag{5.10}$$

Table 5.5.1: Parameters Lady Anna Several Situations

	Diesel manned	*Electric manned*	*Electric Autonomous 5% Δ decrease*	*Electric Autonomous 10% Δ decrease*	*Electric Autonomous 15% Δ decrease*
Installed power	749 kW	749 kW	724 kW	698 kW	672 kW
Displacement	4445 tonnes	4445 tonnes^1	4223 tonnes	4001 tonnes	3778 tonnes

(1) Refers to the situation where the weight of the propulsion systems are equal (diesel vs. electric)

The smaller displacement not only results in a smaller brake power, but also a lower energy consumption. The weight and volume figures in chapter 3 are presented again for the new displacements. An overview of the weight for all five situations is shown in figure 5.5.1. In figure 5.5.2, the volume comparison is shown. It must be kept in mind here, that only the differences in propulsion powers and energy are shown. For the complete design, a larger reduction is expected for autonomous vessel, since not only a decrease in propulsion power is realised.

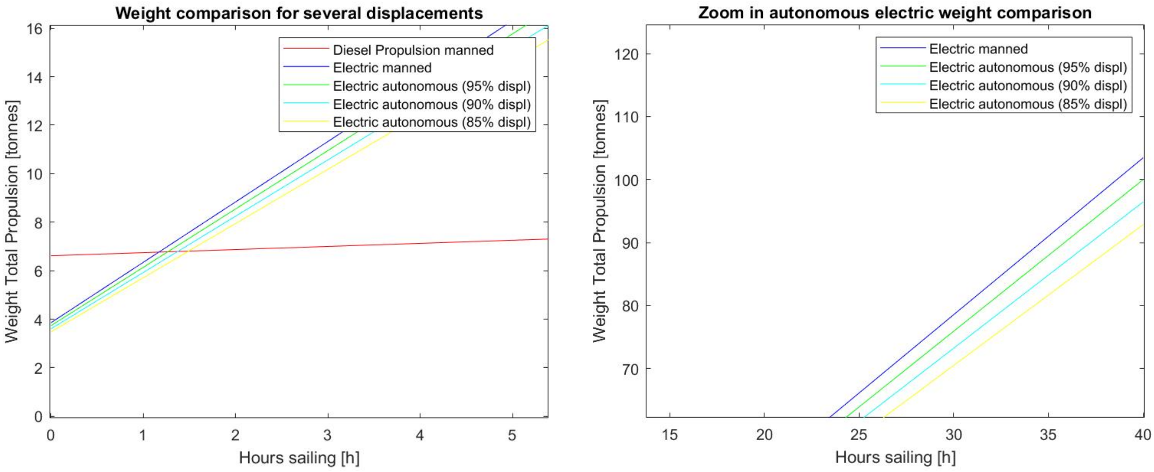


Figure 5.5.1: Weight - Lady Anna operational change due to autonomy over range

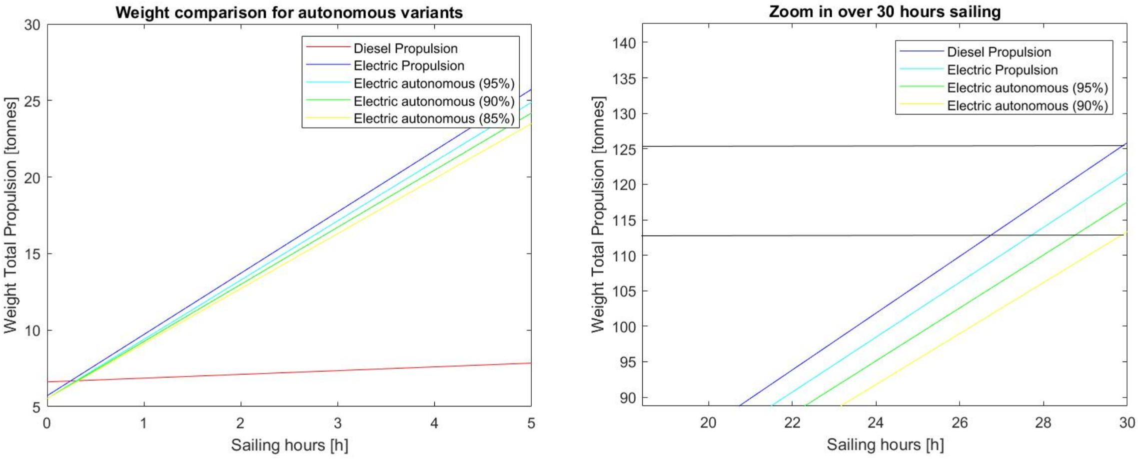


Figure 5.5.2: Volume - Lady Anna operational change due to autonomy over range

From these figures it is concluded that the larger the displacement decrease, the larger the advantage of autonomous shipping. This results in both a volume and weight decrease for the propulsion system. It is also concluded that the advantage of autonomous shipping increases for more hours of operation. The advantage over 30 hours sailing is larger than for 10 hours of sailing. This is due to the lower power needed to reach the same speed. The difference with the diesel arrangement however, is still large. For an arrangement designed for only 5 hours sailing the weight is 15.7 to 18 tonnes more for the reduced displacements. This additional weight increases the draft again, what results in a smaller benefit for the autonomous operation.

The turning point where electric propulsion is favourable over diesel propulsion moves as well. As can be seen in the figures, the crossing point of the red line, the vessel with diesel propulsion, moves to the right for lower displacements. In figure 5.5.3 this is shown in more detail. For a displacement of 85 % of the original manned variant, in increase of 0.3 hours sailing can be obtained, for the volume this is equal to 1 hours. This seems not a significant increase, however if the total range is considered, an increase of $\frac{1.5}{1.2} = 25\%$ for weight and $\frac{8}{7} = 14\%$ for volume is obtained. From that point of view the increase is quite significant.

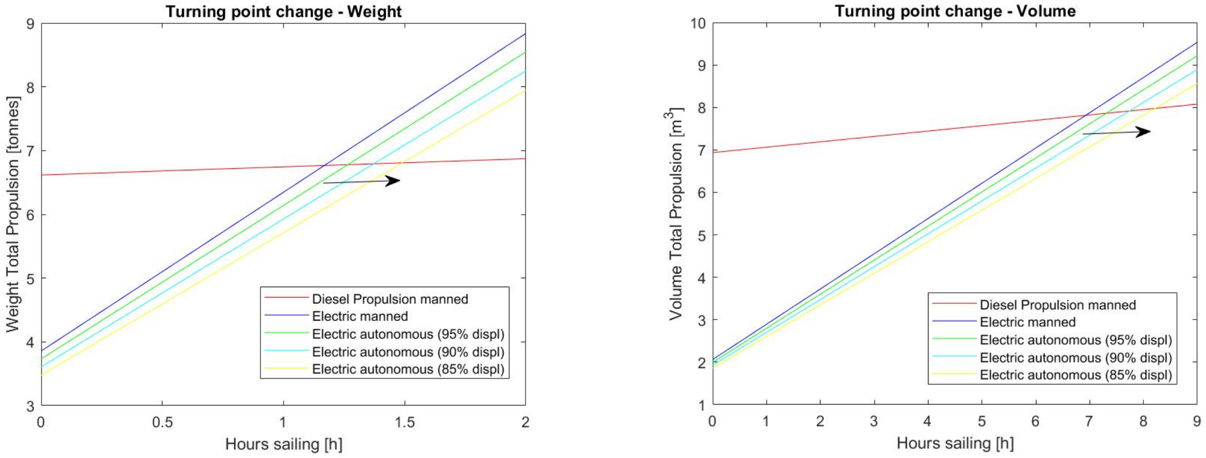


Figure 5.5.3: Turning point changes over the different displacements

5.6. Conclusion Consequences Ship Design

An answer to the fourth and fifth sub-question is presented:
· *What effect do the additional systems and design requirements have on the total ship design? How big are these effects?*
· *How does full autonomy change the operational performance of electric vessels?*

In this chapter it is concluded that the autonomous vessel variant of a manned vessel has a different lightweight, displacement and draft. These changes results subsequently in a change in power requirement, energy consumption and trim.

Furthermore, a decrease in draft realises a decrease in power which increases the operational performance. For the Lady Anna, the example vessel, it is proved that the autonomous vessel variant is more efficient.The draft decrease realises a lower power requirement and a decrease in weight and volume for the propulsion system.

To conclude whether the change in ship design and operation have a positive effect on the economics of a vessel, chapter 6 presents a cost analysis.

6

Cost Analysis

This chapter describes all cost related to changing from an electric manned to an electric autonomous vessel. The chapter uses the results from chapter 5 as input. As shown in figure 6.0.1, the consequences on ship design and operation relate to a change in overall cost. Since this research is focused on the differences in cost between an unmanned and manned vessel, only the expenses and savings that differ between the manned and autonomous vessel are considered in more detail.

This chapter answers both the fifth and sixth sub-question:
· *What are the (operational and design) cost that arise from removing the crew of board?*
· *What are the (operational and capital) savings of a battery powered autonomous vessel in comparison with the manned battery powered variant?*

The results of this chapter are used to identify the parameters that effect the economical viability. With the equations in this chapter it must be possible to calculate the overall capital and operational cost decrease or increase. These results are used in chapter 7, where a detailed discussion on operational conditions is performed.

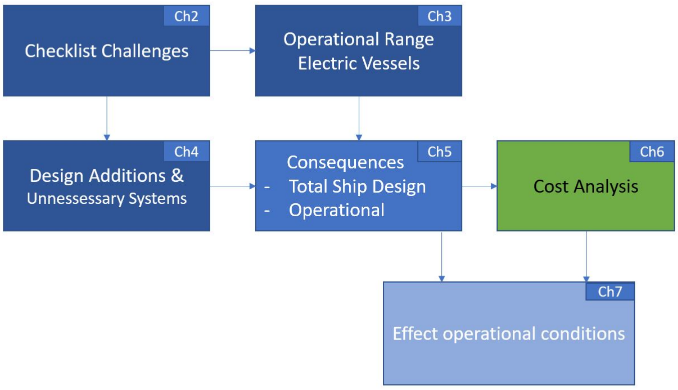


Figure 6.0.1: Overview Research

In section 6.1 of this chapter the cost categories are discussed in more detail. In section 6.2 the difference in capital cost are shown and discussed, where after section 6.3 presents the changes in operational cost. Section 6.4 summarizes the results.

6.1. Design and Operational Expenses

In this research the capital (CAPEX) and operational expenses (OPEX) of the vessel are considered.

No changes in insurance and administration cost are presented. In the chapter 9 recommendations for these cost are given. They are not included since it is unknown whether these cost will increase or decrease.

This section presents an overview of all cost related to the vessels' design and operation. An expectation of the change in cost for autonomous vessels is shown in table 6.1.1.

Table 6.1.1: Identified changes in cost for autonomous vessels

Capital Cost	
Accommodation	-
Hotel/crew systems	-
Redundant propulsion	+
Redundant communication/navigation	+
Autonomous ship technology + systems	+
Operational Cost	
Crew wages	-
Operational performance	-
Hotel systems	-
Maintenance and repair	+/-
Shore Control Center	+

The autonomous variant and operation of a vessel is attractive in cost perspective if the savings in this table are higher than the expenses. To determine the capital and operational expenses the following sections are set up. All cost related to the systems in chapter 4 and the consequences in chapter 5 are identified.

6.2. Capital Cost

The total capital cost consist of all cost related to the ship design. In this section only the cost increase or decrease compared to the manned variant are discussed.

6.2.1. CAPEX Increase: Additions

The additional systems to operate autonomous and the changes in power, do have a significant influence on the economical viability of the vessel. The additions to the navigation, communication, mooring/locking, fire protection and ICT are discussed.

Navigation Additions

As concluded in chapter 4, additional radars, a camera and sound-receivers are necessary to perform the navigation tasks safely. An overview of their cost is shown in table 6.2.1. For all expenses found in literature and expressed in USD a conversion rate of 0.83 is applied, as for 31 April 2021 [107].

Table 6.2.1: Navigation additional cost

System	*Cost (€)*	Lifetime (years)
X-band radar [4],[10]	€12,120	25 years [22]
S-band radar [4]	€5,537	25 years [22]
Camera's [102]	€2,100	5 years
Sound-receiver (4x) [90]	$4 \cdot$ €1,120	5 years

Mooring or Locking Arms

The price for robot arms is not available online. Therefore an estimation is based on smaller industrial robots [78], [6], [50]. The robot has a relatively small payload, but large reach. In addition, the software and arm must be developed for the specific vessel. A cost range of €50,000 to €100,000 is assumed realistic.

Communication Additions

The cost for the communication systems depends on the range the vessels sails from the shore. Both VSAT, Iridium and Wi-Fi connector expenses are shown in table 6.2.2.

Table 6.2.2: Communication additional cost

System	*Cost (€)*	Lifetime (years)
VSAT connection [46]	€49,069	10 years [46]
Iridium connection [33], [2]	€7,707	5 years [46]
WiFi Receiver	€200	5 years

ICT

The software and hardware for all autonomous operations is also difficult to predict. In the MUNIN project the software for the SCC is estimated on €750,000. This is for a situation room for the observation and navigation for several vessels. This is therefore not representative for this research. Based on experts opinion the cost for ICT software is set to €100,000.

Fire-protection Wall

The additional fire protection wall to prevent fire to spread over all batteries has a small contribution to the increase in cost. The cost for one ton of steel (C_{steel}) varies over time. For this research a value of 1730 €/tonnes steel is applied for steel in 2021 [68].

Aerosol Fire-protection

Aerosol systems are more expensive because no water is used. A factor 1.4 is used in contrast with the original water based firefighting system [92]. This is shown in equation 6.1. The cost for the firefighting ($C_{firefighting}$) are all systems excluded the system in the accommodation. The firefighting in the engine room will be the most significant contributor here.

$$C_{aerosol} = 1.4 \cdot C_{firefighting} \quad [€] \tag{6.1}$$

6.2.2. CAPEX Decrease: Savings

In this section all systems and equipment that cause a cost reduction for the autonomous vessel are discussed. Most of these removals are related to the accommodation.

Accommodation

With the removal of the accommodation several cost reductions are realised. Not only a significant weight of steel is removed, also HVAC systems, cables and crew related equipment is removed. Their cost reduction is discussed in this section.

Steel and Joinery

Frijters [42] expresses the cost for steel and joinery as the material and installation cost combined. This is shown in equation 6.2. As shown in this equation, the higher the weight of the steel ($W_{acco,steel}$), the higher the cost reduction. For larger accommodation sections, a higher cost reduction is realised. In addition, some steel will be lost due to cutting. This scrap material is added to equation 6.3.

$$C_{st} = C_{\text{st,material}} + C_{\text{st,installation}} \quad [€] \tag{6.2}$$

$$\begin{gathered} \text{scrap} = 12 + \left(\left(\frac{W_{acco,\text{steel}}}{1.0 \cdot 10^3} + 100 \right)^{-5.3} \cdot 54 \cdot 10^{10} \right) \quad [\%] \\ C_{st,\text{material}} = C_{steel} \cdot W_{acco,\text{steel}} \cdot (1 + scrap/100) \quad [€] \end{gathered} \tag{6.3}$$

The cost for the installation ($C_{st,installation}$) are dependent on the man-hours salary. Frijters [42] applied a value of €50 per hour. The total cost for installation is now given by equation 6.4.

$$C_{st,\text{ installation}} = 4.33 \cdot 10 \cdot W_{acco,\text{steel}} \cdot (1 + \frac{scrap}{100}) \cdot \left(45.36 \cdot \left(\frac{l_{acco} \cdot b_{acco} \cdot h_{acco}}{10^3}\right)^{-0.115} + 3.5\right) \quad [€] \tag{6.4}$$

The cost for the joinery material and installation are dependent on the accommodation surface (A_{floor}). The equations as found by Frijters [42] are shown in equations 6.5, 6.6 and 6.7.

$$C_{\text{Joinery}} = C_{\text{Joinery,material}} + C_{\text{Joinery,installation}} \quad [€] \tag{6.5}$$

$$C_{\text{Joinery,material}} = 7.5 \cdot 10^2 \cdot A_{\text{floor}} \quad [€] \tag{6.6}$$

$$C_{\text{Joinery,installation}} = 1.25 \cdot 10^4 \cdot A_{\text{floor}}^{0.55} \quad [€] \tag{6.7}$$

For the accommodation size of Lady Anna, a cost of € 235,000 is found.

HVAC

The HVAC system in the accommodation is removed. The accommodation in the rest of the vessel is still available to be able to do repairs or maintenance when moored. As found by Frijters [42], the HVAC cost are given by equation 6.8.

$$C_{HVAC} = 2.1 \cdot 10^5 \cdot \left(\frac{l \cdot b \cdot h_{Acco}}{1.2 \cdot 10^3}\right)^{0.65} \quad [€] \tag{6.8}$$

For the Lady Anna the total HVAC cost is €119,000.

Cables and Wires

The cost for cables and wires is given by the amount (S_{cables}) and their cost, as shown in equations 6.9 and 6.10.

$$S_{\text{cables}} = 2.86 \cdot 10 \cdot A_{\text{floor}} \quad [m] \tag{6.9}$$

$$C_{\text{cables}} = 148.23 \cdot S_{\text{cables}}^{0.8469} \quad [€] \tag{6.10}$$

For the Lady Anna the cost for cables and wires removed in the accommodation section are €225,000.

Windows

The accommodation section has several windows. The cost per window ($C_{windows}$) is estimated to be approximately €375 [42]. The installation cost is approximately €500 per window. Equation 6.11 is applicable now. $N_{windows}$ represent the number of windows.

$$C_{windows} = N_{windows} \cdot 875 \quad [€] \tag{6.11}$$

For the Lady Anna, 20 windows of 750 x 500 mm are used. This results in a reduction of €17,500.

Fresh Water and Sanitary Systems

Fresh water is supplied by piping. The cost consists of material and installation expenses. No exact numbers are given for the Lady Anna since the cost are highly dependent on the size and cost for the piping itself. The installation cost are given in equation 6.12.

$$C_{freshwater,installation} = 1.38 \cdot 10^2 \cdot l_{acco} \cdot (b_{acco} + h_{acco}) \quad [€] \tag{6.12}$$

For the Lady Anna this results in installation cost of €27,600. The cost for the pipes and pumps are approximately €35,000 [42].

Several
Five systems identified by Frijters [42] are not discussed in more detail. Their contribution is significant small. In the research of Frijters they are 1.5% of the total building cost reduction. This number is used to cover the cost for the lighting, firefighting systems, internal communication, entertainment system and piping located in the accommodation section.

Lifeboats

The lifeboats available in the vessels can be removed due to the absence of crew. The expenses vary with the number of persons the boat can carry. An overview is supplied by Frijters [42]. For a lifeboat of 16 persons a cost of € 82,000 is assumed [43].

Battery Size

In case the battery capacity decreases due to a more efficient operation, the capital cost decrease. As shown in equation 6.13, this decrease is equal to the battery price multiplied with the decreased capacity ($Ec_{decrease}$). Over the lifetime of a vessel this amount is even higher. The expected lifetime of the batteries of 10 years is currently the marine standard [5].

$$C_{batterydecrease} = Ec_{decrease} \cdot C_{battery} \quad [€] \tag{6.13}$$

6.3. Operational Cost

The operational cost of the vessel consist of all cost related to the operation. This includes manning cost, insurance, maintenance and repair, administration and energy consumption. In this section the changes in manning cost, the change in power requirement and maintenance and repair are presented.

6.3.1. OPEX Increase: Additions

The additions in operational cost consists of the running cost of the SCC and the possible increase in maintenance cost.

Maintenance and Repair

In chapter 2 it is concluded that reliability is recommended for autonomous operations. In addition to reliability are maintenance and repair also important. Researchers are not convinced whether the maintenance cost increase or decrease. On one side the removed systems decrease the maintenance hours and the need for maintenance decreases, while on the other hand additional maintenance is necessary to keep the reliability level high.

According to Moore Stephens [3] the maintenance cost are approximately 17% of the operational cost. This is however dependent on the ship type. Since the actual increase or decrease is hard to predict, two values are taken into consideration. The results for maintenance cost of 12 % or 22% of the total OPEX are considered. This thus represents a decrease or increase of 5% on total OPEX.

Running Cost Shore Control Centre

In the MUNIN project an extended study is done in the cost for running an SCC. This study is however done for a center monitoring 90 vessels [58] 24/7. In this research only one crew member is standing stand-by during sailing hours. The cost for training and the facility are neglected in this research. The running cost for the SCC in this research consist of both the cost for 1 employee standing stand-by and the energy cost. According to the MUNIN research an operational cost of $116,000 annually per vessel is spend. The running cost in this research will be far less since only 1 vessel is considered and no special facility is build. In consultation with experts on this topic, the yearly salary of a chief officer is used. This is equal to € 50,000 a year. In addition, a yearly cost of € 10,000 is added for running the software.

6.3.2. OPEX Decrease: Savings

The operational savings mainly consists on the reduction in crew cost. In addition the more efficient operation results in a decrease in cost. Some researchers mention the decrease in air resistance [25]. This research however considers relatively small and slow sailing vessel. This saving is therefore neglected.

Cost Manning

For this research the monthly salaries as in table 6.3.1 are assumed [58].

Table 6.3.1: Manning Cost [58]

Pay group	**Total salary per month**
Master	€4,782
Chief Officer	€3,124
Boatswain	€1654
Chief Engineer	€4355

The salaries of the crew do not cover 100% of the crew cost. According to experts an additional 30% is common to add for other costs. The total manning cost are therefore the salaries multiplied with 1.3 [73].

Decrease Power Requirement

The decrease in power, as discussed in chapter 5, realises a more efficient operation. The decrease in power requirement realise a decrease in electric motor cost, and a lower energy consumption. This decrease is dependent on the size of the reduction and the operation. As shown in equation 3.19 two values for energy price are considered, 0.05 and 0.17 €/kWh.

6.4. Conclusion Cost Analysis

In this chapter the changes in capital and operational cost are identified. Sub-questions 5 and 6 are answered:
· *What are the (operational and design) cost that arise from removing the crew of board?*
· *What are the (operational and capital) savings of a battery powered autonomous vessel in comparison with the manned battery powered variant?*

The cost parameters as identified in this chapter are all included in the tool. The capital cost changes in the tool consist of the cost for navigation, communication, mooring and ICT. In addition, the batteries, fire-protection and the removal of the accommodation and equipment cause a difference in capital cost.

Secondly, the operational cost are included in the tool. The operational cost parameters in this thesis that differ between the manned and autonomous vessel are maintenance and repair, the running of the SCC, the manning cost and the cost for energy consumption.

Overall it is concluded that for vessels with a conventional accommodation and operation, a cost reduction is realised. The actual size of the additions and removals is case dependent. The following chapter therefore considers a case study. This case study has the goal to put the cost parameters in this chapter in perspective, and give answer to the research question. The operational conditions are identified and discussed.

7

Discussion on Operational Conditions

This chapter has the goal to both provide an overview of the design and cost changes and identify the operational conditions that affect the economic viability of the autonomous vessel variant the most.

Hereafter sub-question 7 can be answered:
What operational conditions affect the operation of an autonomous vessel most regarding economic viability? And to what extent?

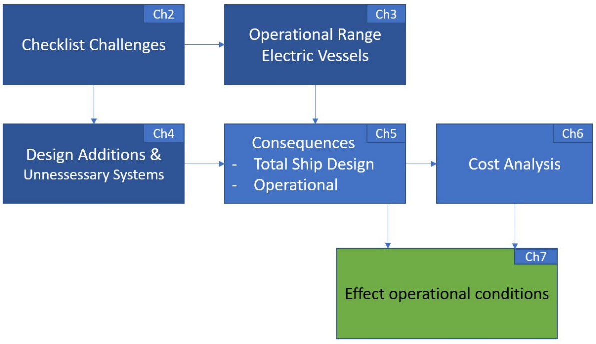


Figure 7.0.1: Overview chapters research

In this thesis it is concluded that for the implementation of autonomous shipping several challenges have to be overcome. It is concluded that an electric propulsion system is favourable over diesel configurations in terms of reliability. In chapter 3 it is concluded that electric propulsion is technical feasible and favourable for relatively small speeds and operational ranges. For high battery capacities (high speeds and/or long sailing distances) the weight, volume and cost are significantly larger compared to diesel arrangements. To be favourable in terms of weight and volume and economical viable, an overall small battery capacity is recommended. In chapter 4 the design changes related to the autonomous operation are discussed. The consequences on displacement, draft, resistance, trim and power are subsequently covered in chapter 5. It is expected that the autonomous vessel operates more efficient. In this chapter the operational conditions that affect the economical viability most are identified. This is done with the input in ship design and operation in chapter 5, and the cost analysis in chapter 6. An overview is shown in figure 7.0.1.

With the information from the previous chapters a tool is developed. All equations related to weight, power and cost are used to set up this tool. The content of the tool is discussed in section 7.1.1. In section 7.2 a case study is performed which uses the output of the tool. The goal of the case study is emphasized where after the results are given. With the help of this case study the operational conditions are discussed in section 7.3. In this section the operational conditions are identified where after their effect on case I is considered. In the section 7.4 a second case study is performed to see whether similar results on the effect of the operational conditions are found. Lastly, in section 7.5 the conclusions and recommendations on the case studies are given, where after the research question is answered.

7.1. Overview Tool

A tool is developed to calculate the design and cost changes for the autonomous vessel variant of an electric vessel. This section describes the content of the tool. The input from chapters 4, 5 and 6 are used for the structure of the tool. The calculations are done using Excel. An overview of the content of the tool is shown in figure 7.1.1.

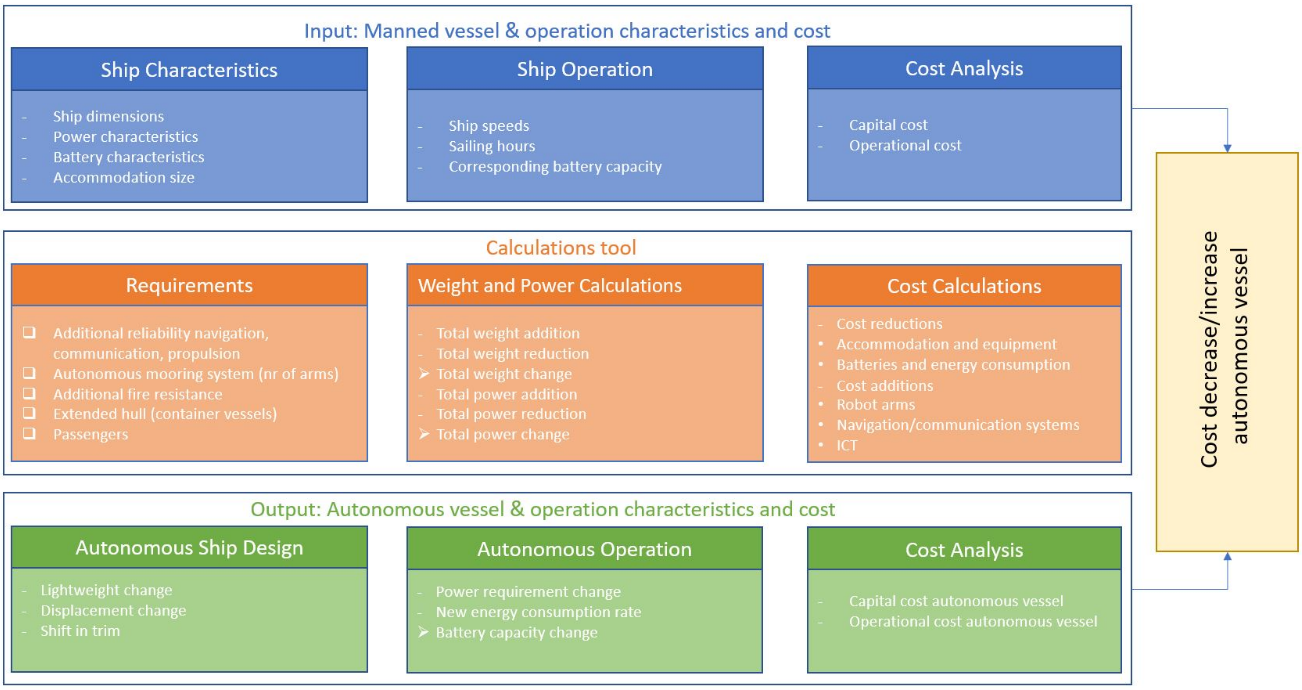


Figure 7.1.1: Overview own tool

The goal of the tool is to provide the autonomous vessel variant of a manned electric vessel. In addition, the tool is able to calculate the cost of the autonomous variant. With this information the research question is answered.

The tool consist of three parts. The input, tool calculations and output. The following sections clarify these parameters separately.

7.1.1. Input Tool: characteristics manned vessel

The tool input consist of all design and operation parameters of the manned electric design. The vessels characteristics like dimensions, displacement and installed power must be entered in the Excel tool. Also the size of the accommodation and battery characteristics are a required input. The following characteristics are entered:

- Dimensions vessel
- Propulsion characteristics
- Battery characteristics
- Steel characteristics
- Accommodation characteristics
- Crew related equipment characteristics

Furthermore, the power characteristics and operation are entered as input for the ships operational performance. These consist of:

- Power and speed characteristics
- Mooring and locking characteristics
- Number of crew members
- Hotel load

With these characteristics the tool is able to calculate the required powers and battery capacity. Lastly, the capital cost and operational cost of the manned vessel are required. These parameters are used as basis for the cost comparison.

7.1.2. Calculations and Requirements Tool

The tool is calculating the autonomous variant of a manned electric vessel. In the research it is concluded that some additional systems are required to sail autonomous. These systems are added in the tool. Also the unnecessary systems are considered and their power, volume and weight characteristics are included in the tool.

Some of the requirements are case dependent. For example the hull extension for container vessels. These systems are added to the tool, and linked to the input parameters. In case they are not applicable, they will give a zero value and have therefore no influence.

The equations as discussed in chapter 4 provide an overview of all additional weights, volumes and powers.

With the provided ship design characteristics the changes in cost are calculated. The equations from chapter 6 are applicable here. The systems added to the design are also linked to their cost. In conclusion, an overview of several cost reductions and additions is provided.

7.1.3. Output Tool: Autonomous Vessel Design, Operation and Cost

As described in chapter 5, the change in weight and power requirements result in a change in total ship design. With the equations provided in this chapter the lightweight, displacement and trim change are calculated. In addition, the change in the vessel operational performance is considered. The new power requirement results in a change in energy consumption. The tool therefore calculates the new power requirements and provides the battery capacity of the autonomous vessel variant.

The consequences on ship design and consequences result in a change in capital and operational cost. To obtain the capital and operational cost of the autonomous design, the cost of the new and removed systems are added, and the operational performance is included. These result in a new capital and operational cost.

7.1.4. Cost Analysis

The output of the tool provides the cost related to the autonomous variant of the electric vessel. With the conventional cost the tool is able to calculate the economic viability. It is possible to identify the significant factors and see whether a cost reduction is realised.

7.2. Case Study I

With the developed tool it is possible to calculate the changes in both design and operation of a vessel. With this information a case study is performed in order to provide an overview of the consequences on both cost and design. With the results of this case study operational conditions are identified, where after their influence is tested. This section describes the input and output of the case study.

The ship used for this case study is a dredger. The clients are convinced this operation is technical feasible and favourable for the following reasons:

- The case is considering a vessel within a port. This means the vessel is always sailing within human reach and the extent of control is high. In case of failures the impact is relatively small and it can quickly be assisted.
- The regulational barriers are expected to be solved easier since the vessel is only sailing within ports. In addition, the vessel is a dredger. Dredging vessels do not have to give way during dredging. This might make the navigation software easier to implement.
- The vessel sails on slow speeds. This means a longer reaction time is possible during manoeuvring or emergency situations.
- In the port no high waves occur which simplifies the autonomous operation.
- No bridges, dams or locks are passed.
- Relatively small trips are sailed since the port area is limited.

7.2.1. Input: Ship and Operation Characteristics

A special dredger is used to operate in a Port. The vessel is not performing a common dredge operation. Instead of re-position the soil layer, it 'recirculates' the soil on deck. The recirculation process involves soil which flows through the ship to come in contact with oxygen. The density of the soil decreases after which it is dumped on the waterbed again. This lower soil density makes it possible for vessels to sail through the layer. The dredger thus guarantees that the soil layer is not to dense to sail trough. In total an area of $3 \cdot 10^6 m^3$ silt per year is recirculated.

A general arrangement of the vessel is shown in figure 7.2.1.

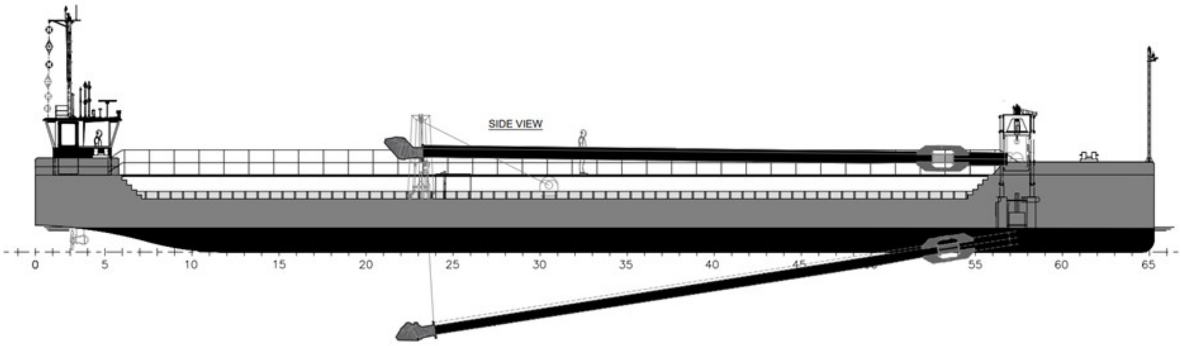


Figure 7.2.1: Recirculation Dredger[Conoship International]

Ship Characteristics

[1] The vessel is relatively small compared to other dredgers and has a low sailing speed. The ship characteristics are shown in table 7.2.1.

Table 7.2.1: Ship Characteristics

L	**B**	**T**	∇	Δ	$Vs_{dredging}$	Vs_{max}
40 m	10 m	1 m	352 m^3	352 tonnes	2 knots	4 knots

The ship carries an accommodation section for three crew members with the dimensions as shown in table 7.2.2.

Table 7.2.2: Accommodation characteristics

h_{acco}	l_{acco}	b_{acco}	$nr_{decksacco}$	$V_{flowacco}$	X_{acco}
5 m	6.1 m	8 m	2	1.5 m^3/h	-18 m (from CoF)

The vessel carries Lithium-Ion batteries with a specific energy of 220 kWh/tonnes and an energy density of 600 kWh/m^3. The price of the battery in 2020 is 113 €/kWh in 2020 and 91 €/kWh for 2021.

Power Characteristics

The vessel has a power installed whereby it can sail 4 knots. The corresponding brake power is 188 kW. For the calculation of the required battery capacity figure 7.2.2 is used. The power required is dependent on the ship speed. The total battery capacity used for the propulsion in terms of ship speed is given in equation 7.1.

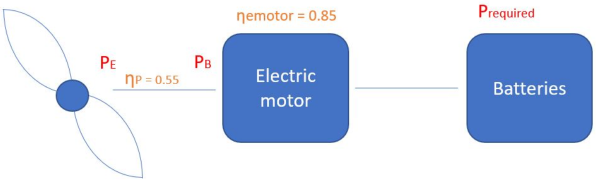


Figure 7.2.2: Overview Powers and Efficiencies - Electric Dredger

$$Ec_{propulsion} = h_{sailing} \cdot \frac{P_e}{\eta_p \cdot \eta_{emotor}} = h_{sailing} \cdot \frac{c1 \cdot v_s^3}{0.55 \cdot 0.85} \quad [kWh] \tag{7.1}$$

The total battery capacity is subsequently given by the amount of power required for the propulsion ($Ec_{propulsion}$), hotel load and dredging operation over the time.

Operational Characteristics Vessel

The ship sails in trips of 8 hours, for 350 days a year. [2] It dredges with a ship speed of 2 knots and sails towards the location with 4 knots. The ship operation and leading times are shown in table 7.2.3 and figure 7.2.3.

This operation is repeated 350 times a year over 25 years. With the power requirements known, the battery capacity is determined. The calculated battery capacity in table 7.2.3 is not the total battery capacity. To prevent the battery from being fully charged or discharged a state of charge of 70% is applied. This results in a total battery capacity of 1051/0.7=1501 kWh. The battery pack is divided over two rooms with each 751 kWh.

For this operation a master, chief engineer and chief officer are operating the vessel.

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[1] The ship characteristics, the input in the tool, are provided by Conoship International

[2] Provided information by Conoship International

Table 7.2.3: Operation Characteristics Recirculation Dredger

Hours	Operation	Speed & Brake Power	Pump Power (dredging)	Mooring Power	Average Hotelload	Required Power	Total Consumption
0.5 hrs	Sailing	4 knots, 160 kW	0	0	0	188 kW	94 kWh
8 hrs	Hotel	2 knots, 0 kW	0	0	9 kW	10 kW	75 kWh
7 hrs	Dredging	2 knots, 20 kW	87 kW	0	0	126 kW	881 kWh
0.5 hrs	Mooring	0 knots, 0 kW	0	2 kW	0	2 kW	1 kWh
8 hrs	All						1051 kWh

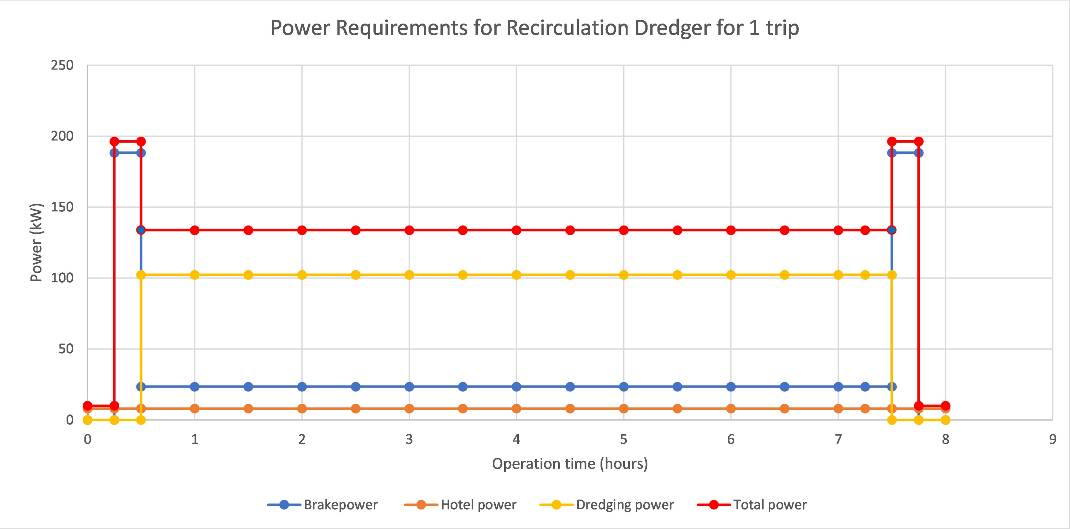

Figure 7.2.3: Power requirements during trip

7.2.2. Input: Cost Characteristics Manned Vessel

In the cost analysis in chapter 6 the change in cost for an autonomous vessel are described. To show the influence of these cost on the total capital cost, a pie chart is composed. For the conventional vessel the capital cost over the lifetime of the vessel are € 5,000,000. The calculated total cost for the accommodation, equipment in accommodation, batteries and the electric motors are approximately 25% of this total cost. The capital cost for the materials and building of the vessel cover the other 75% of the capital cost. This is shown in figure 7.2.4.

The operational cost of the vessel consists of the crew wages, maintenance and repair, energy consumption cost, stores, insurance and administration cost. For this vessel the power requirements are relatively low, which means the crew wages are a significant part of the operational cost. The cost for manning, energy consumption and maintenance are calculated in the tool. The other operational cost are estimated based on several vessels in the Moore Stephens database [3]. As shown in figure 7.2.5, the crewing is 35% of the total operational cost. Over the lifetime of the vessel the total operational cost are € 10,400,000. The operational cost are therefore twice as large as the capital cost over the 25 years.

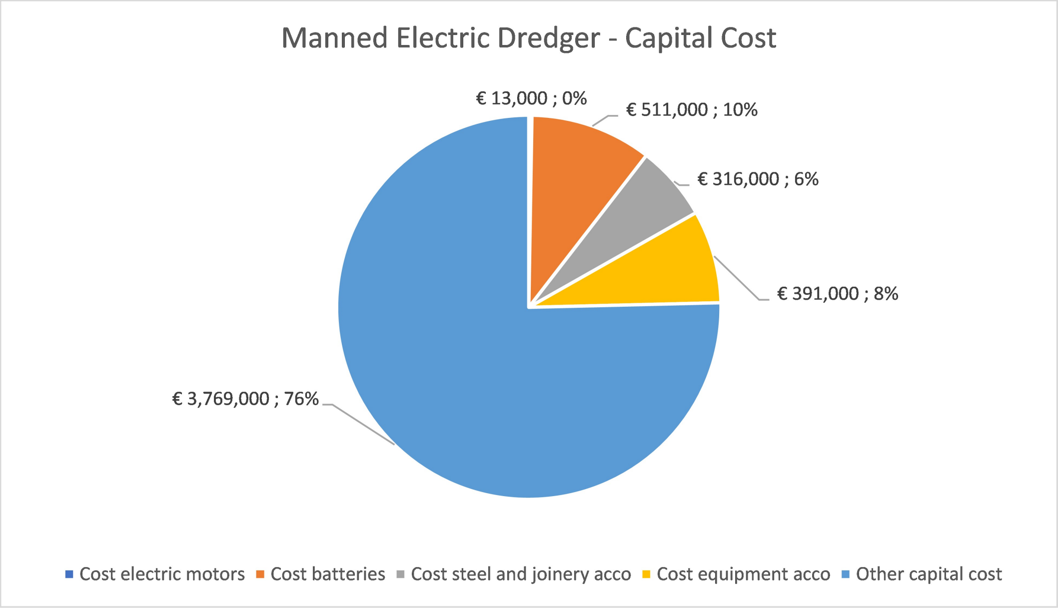

Figure 7.2.4: Capital Cost - Manned Dredger

The tool provides the changes for the autonomous variant of this vessel. In the following section the changes to the design and consequences are described, where after a cost analysis is provided.

7.2.3. Output: Ship and Operation Characteristics Autonomous Vessel

Due to the removals and the additions as described in chapters 4 and 5, a new ship design is obtained. This ship design has a constant length and width, but a different weight (distribution), different power and different energy consumption. The changes related to these elements are shown in table 7.2.4.

Table 7.2.4: Results weight, power, energy, layout from Tool

System	**Weight (tonnes)**	**Maximum Power (kW)**	**Layout**
Navigational additions	-	36.3*	radars, camera and soundreceivers on deck
Communicational additions	-	1.4	Wi-Fi receiver on deck
Additional reliability and fire protection battery packs	0.5	0	2 m^3 additional battery rooms space
Accommodation	- 35.5	- 24.3	accommodation removed
Mooring arms	11 [4 arms]	10	on deck 4 sides
Several (hotel) Equipment	-8.9	-10	mostly in accommodation
Totals	**-32.9**	**- 22.9**	

[*] Navigational additions are back-up systems. It therefore has no effect on the peak power and energy consumption of the vessel.

With the results in table 7.2.4 it is concluded that a decrease in weight and power is realised. This means the ship requires a smaller electric motor and battery capacity. All consequences are discussed in the following section.

Consequences Ship Characteristics

The addition in weight, power and energy consumption results in new ship characteristics. With the equations discussed in chapter 5, the results as shown in table 7.2.6 are obtained.

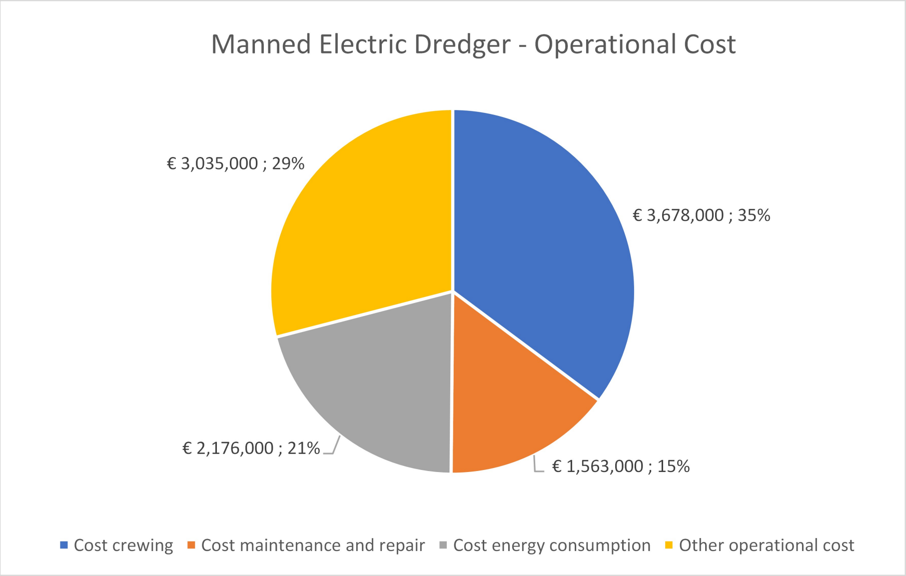

Figure 7.2.5: Operational Cost - Manned Dredger

Table 7.2.6: Ship Characteristics

	L	**B**	**T**	Δ	v_s dredging
Manned	40 m	10 m	1 m	332 tonnes	2 knots
Autonomous	40 m	10 m	0.9 m	299 tonnes	2 knots
Δ			-0.1 m	- 32.9 tonnes	

Consequences Power

The change in resistance leads to a change in installed power. In addition, the hotel load is removed, but the added systems need a little power, as shown in table 7.2.7.

Table 7.2.7: Power characteristics - autonomous

	$Pb_{installed}$	P_{pump}	$P_{maxhotelload}$	$P_{mooring}$
Manned	188 kW	102.3 kW	10 kW	0
Autonomous	173 kW	102.3 kW	1.4 kW	10 kW
Δ	-15 kW	-	-8.7 kW	+ 10 kW

This results in the new power characteristics as shown in figure 7.2.6.

Consequences Energy Consumption

The change in power requirements result in a change in battery capacity. The difference in battery capacity is the difference in the area between the lines of figure 7.2.6. In addition, to have extra reliability, the battery packs are split up in two parts as shown in table 7.2.8. In this case no additional losses occur, the total efficiency is therefore constant.

Table 7.2.8: Battery characteristics

	$Ec_{battery}$	Ec_{total}	$V_{batteries}$	$W_{batteries}$	$C_{battery}$
Manned	752 kWh (2x)	1504 kWh	2.5 m^3	6.8 tonnes	€ 170,000
Autonomous	348.3 kWh(4x)	1393 kWh	2.3 m^3	6.3 tonnes	€ 158,000
Δ		-111 kWh	-0.2 m^3	- 0.5 tonnes	€ 13,000

As shown in the table the autonomous operation is more efficient. A smaller battery capacity E_c is necessary, and a cost reduction is realised.

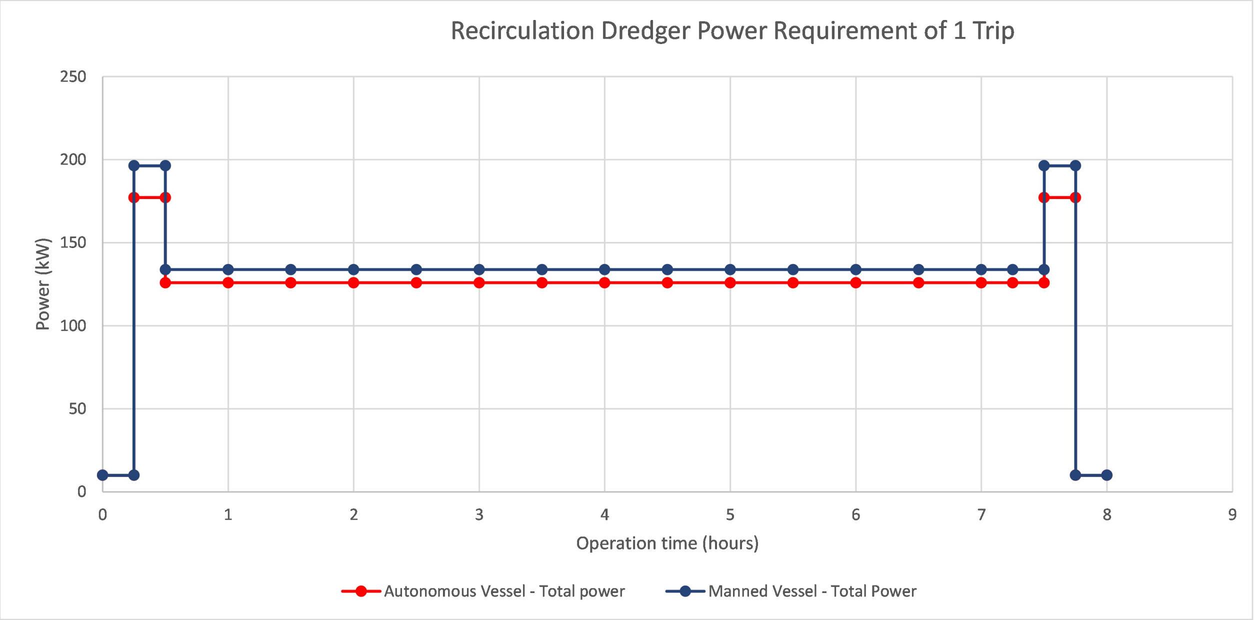

Figure 7.2.6: Recirculation dredger powers autonomous vs manned variant

Consequences on Trim

The change in weight results in a change in trim. The trim is given with the help of the weights and positions given in table 7.2.9. A trim of -1.9 degrees is obtained using equation 7.2.

Table 7.2.9: Weight and position systems dredger

System	**Weight (tonnes)**	**Position (m)**	**Moment $m \cdot s$**
Additional firewalls/batteries	0.48 tonnes	-5 m (C.o.F.)	- 2.4 m · tonnes
Decrease battery size	-0.5 tonnes	-5 m	2.5 m · tonnes
Accommodation steel and joinery	35.50 tonnes	-18m	-639 m · tonnes
Equipment Accommodation	8.88 tonnes	-18 m	-160 m · tonnes
Mooring arms	11 tonnes [total]	+/- 18 m (ps/sb)	0

$$\alpha_{dredger} = \arctan \frac{m \cdot s \cdot g}{\rho_w \cdot g \cdot \nabla_{new} \cdot GM_L} = -0.03 rad = -1.9 \quad [degrees] \tag{7.2}$$

In the table it is made clear that the removal of the accommodation and equipment have the most effect. The negative trim value does mean the ship is slightly inclined to the stern. This can be solved during the optimising phase of the ship design.

7.2.4. Output: Cost Characteristics Autonomous Vessel

In the following section the cost changes are described. Both capital and operational cost differ for the manned and autonomous vessel design.

Consequences Cost - Capital

In this section all capital cost as in chapter 6 are described. Also the autonomous vessel design cost are included. In table 7.2.10 the difference in cost is shown. The results are given over the 25 year lifetime of the vessel. Two results for the battery cost as shown, the value of 113 €/kWh for 2020 and the value for 2021 of 91 €/kWh.

The table shows that an overall cost reduction of maximal € 504,000 is obtained. The ratio of these cost reductions compared to the manned vessel is given in figure 7.2.7.

Table 7.2.10: Capital Cost changes

System	**Manned cost**	**Autonomous cost**	Δ_{cost}
Electric motors	€ 13,000	€ 12,000	-€ 724
Batteries cost 2020 [2021]	€ 511,000 [€410,000]	€ 473,000 [€ 380,000]	-€ 38,000 [-€ 30,000]
Accommodation steel & joinery	€ 316,000	0	-€ 316,000
Accommodation equipment	€ 402,000	0	-€ 402,000
Cost fire protection	€ 1,000	€ 2,000	€ 1,000
ICT cost	0	€ 100,000	€ 100,000
Navigation additions	0	€ 51,000	€ 51,000
Communication additions	0	€ 1,000	€1,000
Mooring system	0	€ 100,000	€ 100,000
Total	€ 1,244,000 [€ 1,143,000]	€ 740,000 [€ 646,000]	-€ 505,000 [-€ 497,000]

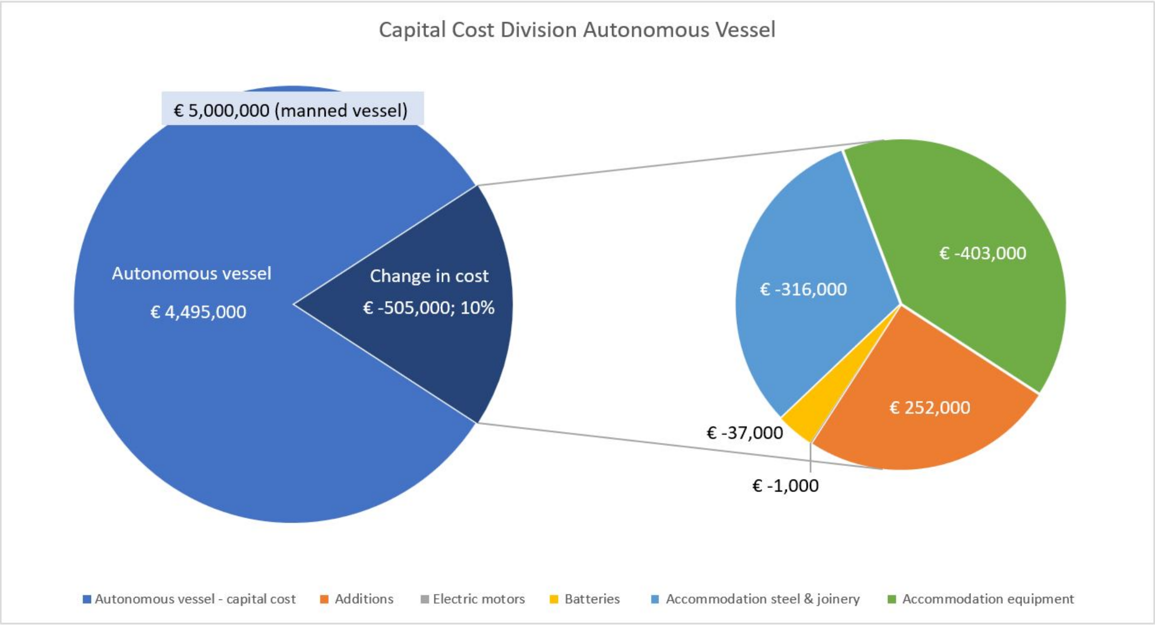

Figure 7.2.7: Capital Cost Reduction Distribution for Case I

In total a reduction of 10% compared to the conventional vessel is realised. The reduction in cost for the electric motors are negligible. The largest reduction consist of the removal of the accommodation and its equipment.

Consequences Cost - Operational

The operational cost as discussed in chapter 6 consist of maintenance cost, manning cost, running of the SCC and the total energy consumption. The rest of the operational cost is assumed constant for the manned and autonomous vessel. For some of the cost parameters two values are discussed. The energy consumption price is fluctuating between 0.05 €/kWh and 0.17 €/kWh. Both values are taken into consideration. For the maintenance an increase and a decrease of 5% are included. For this dredger the results are shown in table 7.2.11 for 25 years of operation.

It can be concluded that an operational cost reduction of € 3,364,000 to € 3,500,000 is obtained. The distribution of the cost reduction is given in figure 7.2.8.

It is shown in the figure that the total operational cost for the autonomous vessel is reduced with 32%. The largest part of the cost reduction is caused by the manning cost.

Table 7.2.11: Operational Cost changes

Item	**Manned cost**	**Autonomous cost**	Δ_{cost}
Manning cost	€ 4,782,000	€ 1,250,000	- €3,532,000
Maintenance and repair	€ 1,563,000	€ 1,641,000 [€ 1,485,000]	€ 78,000 [-€ 78,000]
Running Shore Control Centre	0	€ 250,000	€ 250,000
Energy Consumption	€ 2,176,000 [€ 544,000]	€ 2,015,000 [€ 504,000]	-€ 161,000 [- € 40,000]
Total	€ 8,521,000 [€ 6,889,000]	€ 5,156,000 [€ 3,489,000]	- € 3,365,000 [- € 3,400,000]

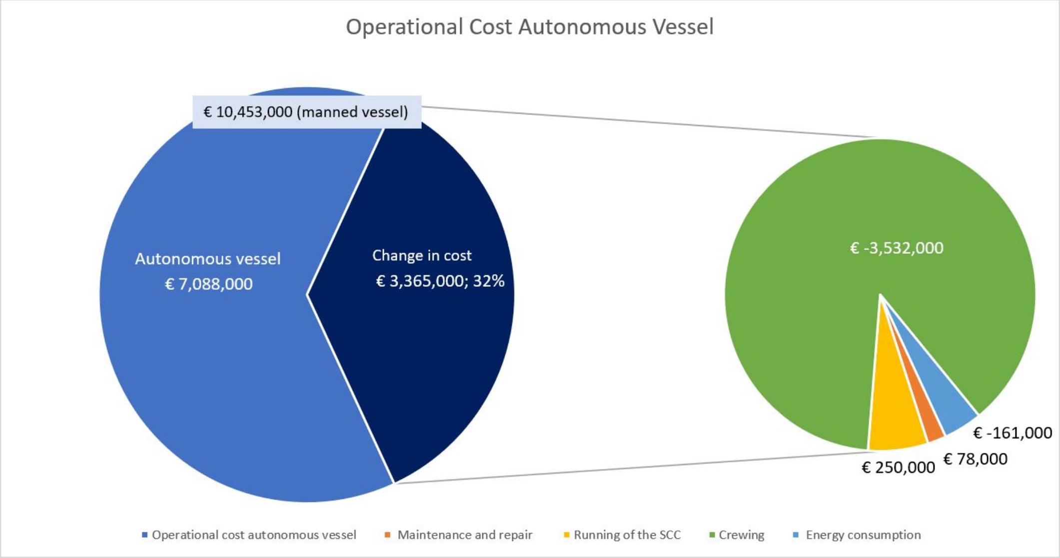

Figure 7.2.8: Operational Cost Reduction Distribution for Case I

7.2.5. Conclusions Case I

This case is performed to provide an overview of the size of the reductions and additions. It is concluded that this case is technical feasible and favourable for autonomous shipping. The results from the case show that both a change in ship design and operation occur. In addition, the autonomous vessel variant is significantly cheaper compared to its manned variant. For this case it is confirmed that the autonomous variant is economical viable and favourable over the manned variant.

Since a high and low value are taken for some parameters, the results are shown in a maximum and minimum value. Overall the following results are obtained for this vessel and operation:

- The total capital cost benefit is € 497,000 to € 505,000
- The total operational cost benefit is € 3,364,000 to € 3,400,000

This results in a total reduction over the lifetime of the vessel of € 3,861,00 to € 3,905,000. This is a total reduction of 25% compared to the manned vessel!

The case results are presented, the effect of the operational conditions is however still unknown. Therefore the operational conditions and their effects are described in the following section.

7.3. Operational Conditions

As concluded in the previous section a cost reduction is realised for the autonomous variant of the vessel. The effect on this cost reduction on four operational conditions are described in this section. It is namely operation dependent what the exact reduction will be. As identified the largest capital cost reduction is realised by the accommodation and equipment. For the operational cost the manning cost is most significant. In this research the operational conditions that are linked to those cost parameters are identified and their effect is tested.

7.3.1. Identification Operational Conditions

The goal of this section is to identify the operational conditions that affect the economic viability.

This is done by looking into the cost analysis from chapter 6. The overall capital and operational cost parameters are interesting, but the research is searching for operational conditions that affect these parameters. With that information a conclusion can be drawn for more types of vessels and different operations.

The following parameters are identified that vary for different vessels and operations:

- The installed power of the installed electric motors
- The battery capacity (and fire resistance walls)
- Cost for the communication system
- The energy cost for the operation
- The size of the accommodation and equipment
- Crew cost

In figure 7.2.7 the cost for electric motors are not significant. The most significant cost factors, the accommodation and equipment, the batteries, energy consumption, manning cost, and the cost for the communication system are included. The operational conditions related to these cost are identified and introduced.

Firstly, a decrease in draft is obtained for the autonomous vessel. This draft is displacement related. Since the length and width of the vessel are constant, the draft variation is equal to the displacement variation. The displacement has influence on the required power and electric motor. The displacement is considered as an operational choice. The '**displacement**' is therefore identified as the first operational condition.

Secondly, different power requirements are applicable for different vessels. The required power is dependent on the ship speed and resistance. The speed, required power and operation time represent the battery capacity. The second operational condition considered is therefore the **battery capacity**.

Thirdly, the cost for the communication system differs for vessels sailing inside or outside the Wi-Fi range. As found in chapter 6 this results in a significant cost difference. This parameter is referred to as '**distance to shore**'.

Lastly, the several expenses are operation dependent. The size of the accommodation and equipment, the crew cost and the cost for the energy are dependent on the operation. The fourth operational condition is therefore '**vessel type and operation**'.

7.3.2. Displacement

In chapter 5 it is concluded that a change in total weight results in a change in ship displacement. It is expected that the total draft will decrease as the weight lowers due to the significant weight of the accommodation. As shown in equation 5.2, a decrease in displacement leads to a decrease in draft. In case of a draft decrease, less power is necessary to keep the same ship speed which results in a decrease in battery capacity. Since the batteries are a significant cost factor, a significant cost reduction for the autonomous vessel is expected.

Displacement Variation

The first operational condition is the displacement. The displacement of the dredger is relatively small. For a change in displacement the following changes occur:

- The dimensions and power requirement of the installed electric motors change

- The battery capacity changes
- The fire resistance wall size changes with the battery capacity
- The energy cost changes for a different consumption

The cost for the batteries and energy consumption are most significant and therefore considered.

A small study is performed to determine the effect of the conventional chosen displacement. This is done by varying the original draft. The results over the lifetime of the vessel are shown in table 7.3.1. The results for the the energy price of 0.17 €/kWh and battery price of 113 €/kWh are presented.

Table 7.3.1: Draft Variation Benefits

T		$\Delta Ec_{battery}$	**Manned cost**	**Autonomous cost**	Δ_{cost}	% Total benefit
1 (0.9) m	$C_{batteries}$	-111 kWh	€ 511,000	€ 473,000	-€ 38,000	
1 (0.9) m	$C_{econsumption}$		€ 2,176,000	€ 2,015,000	-€ 161,000	
					- € 198,000	5.1% *
1.5 (1.4) m	$C_{batteries}$	-109 kWh	€ 550,000	€ 513,000	-€ 37,000	
1.5 (1.4) m	$C_{econsumption}$		€ 2,343,000	€ 2,186,000	-€ 157,000	
					- € 195,000	5.0% ***
0.5 (0.4) m	$C_{batteries}$	-117 kWh	€ 464,000	€ 424,000	- € 40,000	
0.5 (0.4) m	$C_{econsumption}$		€ 1,977,000	€ 1,807,000	- € 170,000	
					-€ 211,000	5.4% ***

* Based on the maximum benefit of € 3.87 million; ** € 3.86 million; *** € 3.88 million

It is concluded that the displacement has effect on the efficiency of the operation and thereby the energy consumption and battery dimensions. For this case, a smaller displacement realises a larger reduction in battery capacity and therefore cost. The percentage of the total benefit is also larger. The difference is however small.

Lessons learnt displacement
For a constant weight and power reduction, the effect on cost decrease is largest for vessels with a small draft. The effect on battery capacity is the largest.

7.3.3. Conventional Battery Capacity Vessel

The battery capacity of a vessels depends on the energy consumption of the systems on board, the propulsion power and the sailing distance. For an increase in ship speed the battery capacity increases. This also applies for sailing distance. It is concluded that a reduction in battery capacity realises a cost reduction. The size of this battery capacity reduction influences the cost decrease. As shown in figure 7.2.4, the batteries are 10% of the total capital cost. A reduction in battery capacity decreases this percentage.

Battery Capacity Variation

In this section two comparisons are done. At first it is expected that the larger the (reduced) hotel load the more efficient the autonomous operation, the larger the cost reduction. Secondly, it is expected that for large battery capacities the largest cost reduction is realised.

Hotel Load Variation

The situation is considered were the manned vessel has more hotel equipment on board. In total 4 kW more power is required. Since this power requirement is removed for the autonomous vessel, the autonomous operation is even more efficient. In table 7.3.3 it is shown that for a hotel load of 12 kW, an amount of 54 kWh of battery capacity is removed. This realises a lower battery and energy consumption cost. In Appendix F a visual representation of the total required battery capacity over the first 7.5 hours of the trip is shown.

Table 7.3.3: Battery Capacity Variation Benefits

	Average Hotelload	$\Delta Ec_{battery}$	**Manned Cost**	**Autonomous cost**	Δ_{cost}	% total benefit
$C_{batteries}$	8 kW	-111 kWh	€ 511,000	€ 473,000	-€ 38,000	
$C_{econsumption}$	8 kW		€ 2,176,000	€ 2,015,000	-€ 161,000	
					- € 199,000	5.0% *
$C_{batteries}$	12 kW	-165kWh	€ 529,000	€ 473,000	-€ 56,000	
$C_{econsumption}$	12 kW		€ 2,253,000	€2,015,000	-€ 238,000	
					-€ 294,000	7.4%**

* Based on the maximum benefit of € 3.9 million ** Based on the maximum benefit of €4.0 million

As shown in the table the original larger hotel load leads to a larger reduction. In addition, the percentage benefit for 12 kW is 7.4% which is larger than the originally 5.0 %.

Lessons learnt hotel load
The hotel load has a significant influence on the power requirement on board. The larger the original hotel power and sailing hours, the larger the cost reduction is for the autonomous vessel. Furthermore, the percentage cost decrease for the hotel load increases for larger hotel load values.

Ship Speed and Range Variation

Both the ship speed, resistance and operational range affect the battery capacity. For a larger ship speed the electric motors increase in size, and a higher battery capacity is needed for the same hours of sailing. For this case a larger ship speed is not relevant, since it still dredges with 2 knots. The situation where the dredger its operational time is extended, is therefore more interesting to consider. For this situation the operation takes 14 hours to complete. This means 6 hours additional dredging and hotel power are required. An additional 1160 kWh is installed which results in an additional 80 kWh reduction for the autonomous vessel. The results on cost are shown in table 7.3.5.

Table 7.3.5: Battery Capacity Variation Benefits

	E_c Conventional	$\Delta Ec_{battery}$	**Manned Cost**	**Autonomous cost**	Δ_{cost}	% Total benefit
$C_{batteries}$	1504 kWh	-111 kWh	€ 511,000	€ 473,000	-€ 38,000	
$C_{econsumption}$	1504 kWh	-111 kWh	€ 2,176,000	€ 2,015,000	-€ 161,000	
					-€ 199,000	5.0%
$C_{batteries}$	2664 kWh	- 191 kWh	€ 905,000	€ 840,000	-€ 65,000	
$C_{econsumption}$	2664 kWh	-191 kWh	€ 3,852,000	€ 3,576,000	-€ 277,000	
					-€ 342,000	8.5%

* Based on the maximum benefit of € 3.9 million ** Based on the maximum benefit of €4.0 million

It is concluded that the battery capacity of the conventional manned vessel has a significance influence on the benefit of the operational vessel. The total reduction in battery increases for larger battery capacities. It is shown that the total percentage benefit is also largest for the vessel with the largest battery capacity.

Lessons learnt battery capacity
Manned vessels with a large battery capacity are potentially most suitable to invest in for an autonomous variant. Both absolute and percentage the cost decrease is largest for larger battery capacities.

7.3.4. Distance to Shore

This parameter is identified for both a safety reason as for the economical viability reason. The smaller the distance to shore the more control can be exerted by the operator. In cases of failure the autonomous vessel can easily be assisted by tugboats or an employee can take over control manually. The possible impact in cases of failure is therefore smaller, and a higher level of safety is realised. For vessels further from shore less control is possible. In addition, the connection with shore is easier and cheaper established.

In this case study the dredger sails within Wi-Fi range. If it would sail outside the Wi-Fi range the cost for a VSAT and Iridium connection are necessary. Instead of €1,000 for the communication system, € 186,000 is spend. The benefit in capital cost for this situation is € 320,000 instead of €505,000. The benefit of autonomous shipping decreases by 37% for sailing outside the Wi-Fi zone. It is therefore beneficial that the dredger sails within the port area were Wi-Fi is available.

7.3.5. Vessel Type and Operation

Different vessel types perform different operations. Some of these operations are more favourable to perform autonomous than others. For example different crane and difficult ballast operations are discouraged for autonomous vessels [99].

Furthermore, the operation of the vessel influences the amount of crew members on board and the accommodation size. In chapter 6 it is concluded that the amount of crew members determine a significant part of the operational cost. The more crew members in the manned vessel, the higher the operational saving is for the autonomous one. It is also concluded that the operation and ship type have a significant influence on the size of the accommodation, which affects the cost reduction. The larger the crew, and the larger the sailing distance, the larger the accommodation section is. For example ships that operate over more than one day, sleeping quarters and facilities are necessary. All these additional accommodation equipment, realise a higher cost reduction for the autonomous vessel.

Crew Size

The manning cost in this thesis are estimated with the information from the MUNIN project. For the dredger only three crew members are on board. For larger crews the operational cost decrease is more significant. If the operation by the manned vessel is done with an additional boatswain, a monthly salary of € 1,654 is added to the operational cost. For the 350 days per year this would mean an additional investment of € 496,000. This would mean an additional operational cost reduction of 13 to 14% (see table 7.2.11). It is however more interesting to see whether there is still an operational cost benefit for a reduced crew.

As shown in figure 7.2.8 the operational cost reduction consist for 95 % of manning cost. This is based on three relatively expensive crew members. In case the crew members have a lower income, the total cost reduction decreases for the autonomous vessel. In table 7.3.7 it is shown that for the situation were only 2 boatswains are crewing the manned vessel, no cost reduction is realised.

Table 7.3.7: Crew Size Reduction Effects

	Manning Cost	Total OPEX	% Manning Cost	OPEX Benefit
Master, chief engineer, chief officer	€ 4,782,000	€ 10,452,000	46%	- € 3,364,000
Master, chief engineer	€ 3,564,000	€ 8,343,000	43%	- € 2,166,000
Master, boatswain	€ 2,510,000	€ 6,520,000	38%	- € 1,130,000
2 x boatswain	€ 1,290,000	€ 4,408,000	29%	+ € 70,000
Crew member(s) X	€ 1,362,000	€ 4,532,000	30%	0

Lessons learnt crewing
It is concluded that the crewing size and salaries have a large influence on the total operational cost reduction. Vessels with a larger and more expensive crew realise a larger cost reduction. This is done under the assumption that the crew member on shore has a salary of € 50,000 a year. For the situation with a reduced crew, there is a cost reduction till a yearly salary of € 54,000 is paid for crew members. For this case this means that for all crew salaries higher than € 54,000 yearly there is an operational cost reduction.

Accommodation Size

As concluded in chapter 4, the weight of the accommodation is significant in comparison with other reductions or additions. The size of the accommodation therefore has a significant influence on the total weight reduction. To put this into perspective the accommodation size of the current vessel is decreased. The current accommodation weight for steel and joinery is 35.5 tonnes. The results for an accommodation weight of 15.5 tonnes is considered. This number seems suitable for a small dredger and is provided by an industry expert.

In table 7.3.8 an overview is shown of the consequences on the size of the accommodation. The cost for the accommodation and equipment change, as well as the battery and energy consumption cost.

Table 7.3.8: Capital Cost changes

System	Benefit for 35 tonnes	Benefit for 15 tonnes
Batteries cost	-€ 38,000	-€ 31,000
Accommodation and equipment	-€ 707,000	-€ 405,000
Cost energy consumption	-€ 161,000	-€ 134,000
Total	- € 906,000 23% (of € 3,869,000)	- € 570,000 16% of (€ 3,533,000)

Lessons learnt accommodation size
It is concluded that the accommodation size is significant for the removed equipment, the batteries and the energy cost. As shown in table 7.3.8 the smaller accommodation realises a cost reduction which is €336,000 smaller than for the accommodation of 35.5 tonnes. Also the percentage cost reduction is largest for the heaviest accommodation. In general applies the larger the accommodation, the larger the cost reduction.

7.3.6. Conclusion on Operational Conditions

The operational conditions displacement, battery capacity, distance to shore and the vessels operation are discussed. It is concluded that all four conditions influence the total economical viability of the vessel.

At first it is concluded that the displacement influences the expense for the electric motors, battery capacity and energy cost for the operation. The higher the percentage displacement decrease, the larger the cost reduction.

Secondly, it is concluded that the battery capacity and its cost are significant. The larger the battery decrease, the larger the cost decrease for the autonomous vessel. The largest cost decrease is obtained for vessels with a large hotel load and original large battery capacity. Thereby it has the most influence if the largest part of this battery capacity is determined by propulsion requirements.

Thirdly, vessels sailing close to shore have significantly lower expense for their communication system.

Lastly, the ships specific operation is of influence. The amount of crew members and the size of the accommodation have a large effect on the new ship design, its operation, and the cost benefit.

A second case study is performed to test these conclusions. This second case study considers the situation of a larger dredging sailing over longer distances. The influence of the operational conditions might increase.

7.4. Case Study II

In this section a second case study is presented. The goal of this case study is to see whether the operational conditions in the first section behave similar for a larger vessel with a larger operational reach. This section describes the input and output values, were after the effects of the operational conditions are discussed.

7.4.1. Input Case Study II

This case study describes the situation for a dredger covering the Port area and the the part outside the locks. An overview of the results is presented in this chapter, the specific characteristics are given in Appendix E.

Ship Characteristics

The vessel has a displacement of 2510 tonnes and a draft of 3 meters. It carries an accommodation of 58 tonnes.

Power Characteristics

The vessel sails towards its location on a speed of 10 knots, which requires a brake power of 713 kW. Dredging is done on 2 knots, and a propulsion power of 78 kW.

Operational Characteristics

The vessel sails trips of 12 hours. It sails 1.5 hours towards its location, where after it dredges for 8 hours and sails back to its station again. In total this requires a battery capacity of 12912 kWh for the manned vessel design. This is quite large for a battery powered vessel, see chapter 3. In this case the client probable attaches more value to electric propulsion than the cheapest operation. It is however interesting to see how much cheaper the autonomous variant of the vessel is. The vessel is sailing with a crew of four. A master, chief engineer, chief officer and a boatswain operate the manned vessel.

Cost Characteristics

The investment and total capital cost over the life time are estimated. The total cost are larger compared to case I. Over the 25 years lifetime of the vessel 7 million on capital cost is assumed. Since the vessel has a significant larger battery capacity, the influence on the capital and operational cost for the batteries and energy consumption is large. As shown in figure 7.4.1 the influence of the manning and accommodation decreases compared to case I.

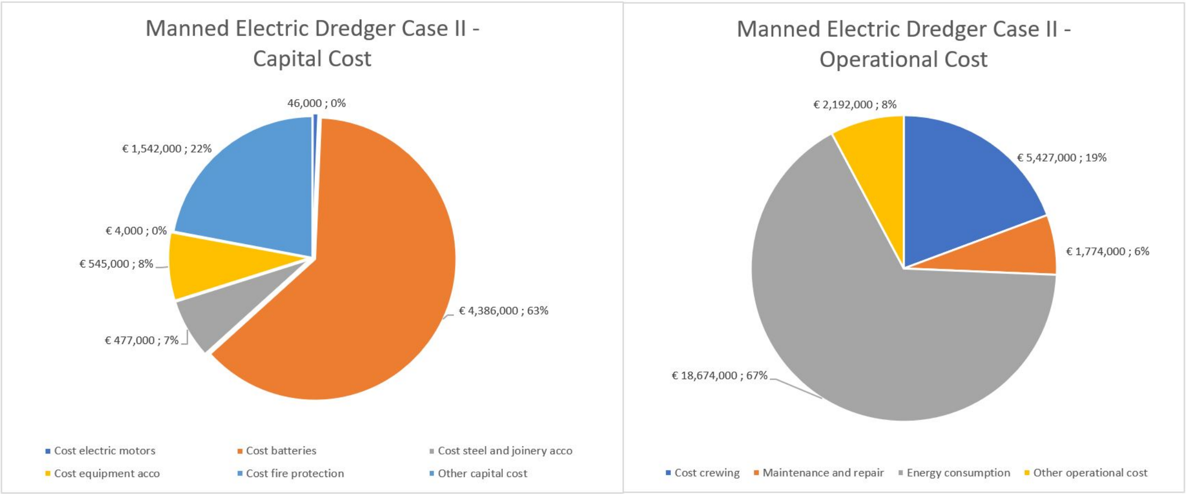

Figure 7.4.1: Capital and Operational Cost Division Dredger Case II

7.4.2. Output Case Study II

The most important conclusions are discussed in this section. The tables related to the numbers are provided in Appendix E.

The autonomous variant of the vessel is more efficient. Its draft decreases with 0.07 m to 2.93 m. In addition, the total battery capacity decreases from 12912 kWh to 12615 kWh. A battery capacity reduction of 297 kWh is realised.

Consequences Cost

Also for this case a cost reduction is realised. The division of the cost is shown in the figures 7.4.2 and 7.4.3.

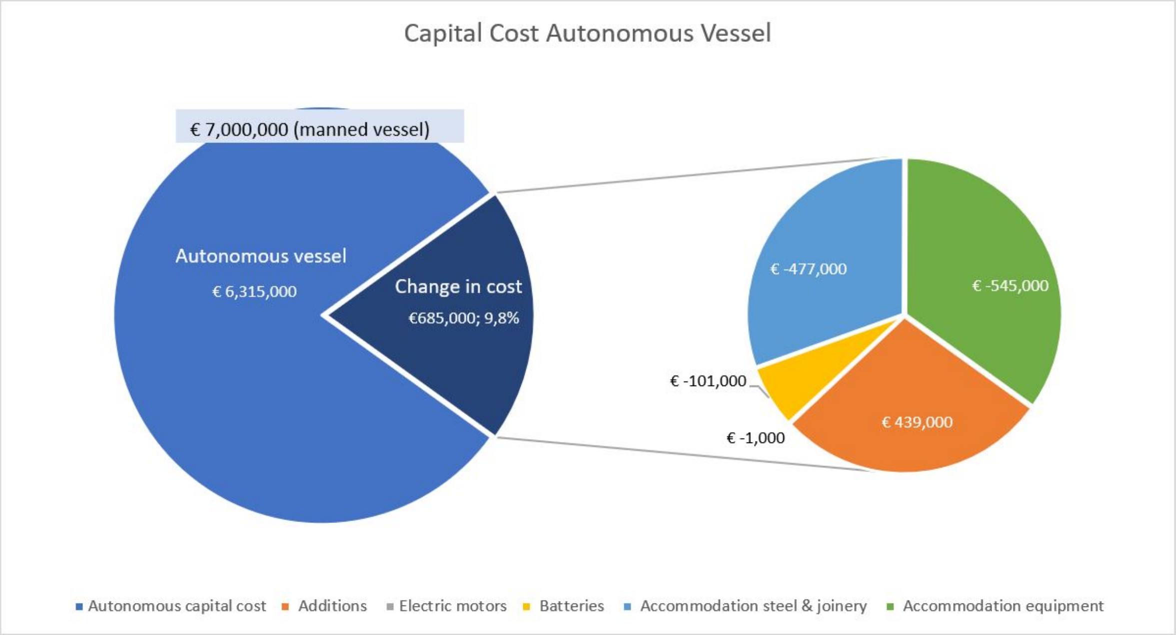

Figure 7.4.2: Capital Cost Division Autonomous Dredger

A capital decrease of 9.8 % compared to the manned variant is realised. This decrease consist of the removal of the accommodation, equipment and the decrease in battery size. An additional € 439,000 in additions is necessary. This number is larger compared to case I since additional communication satellite receivers are installed.

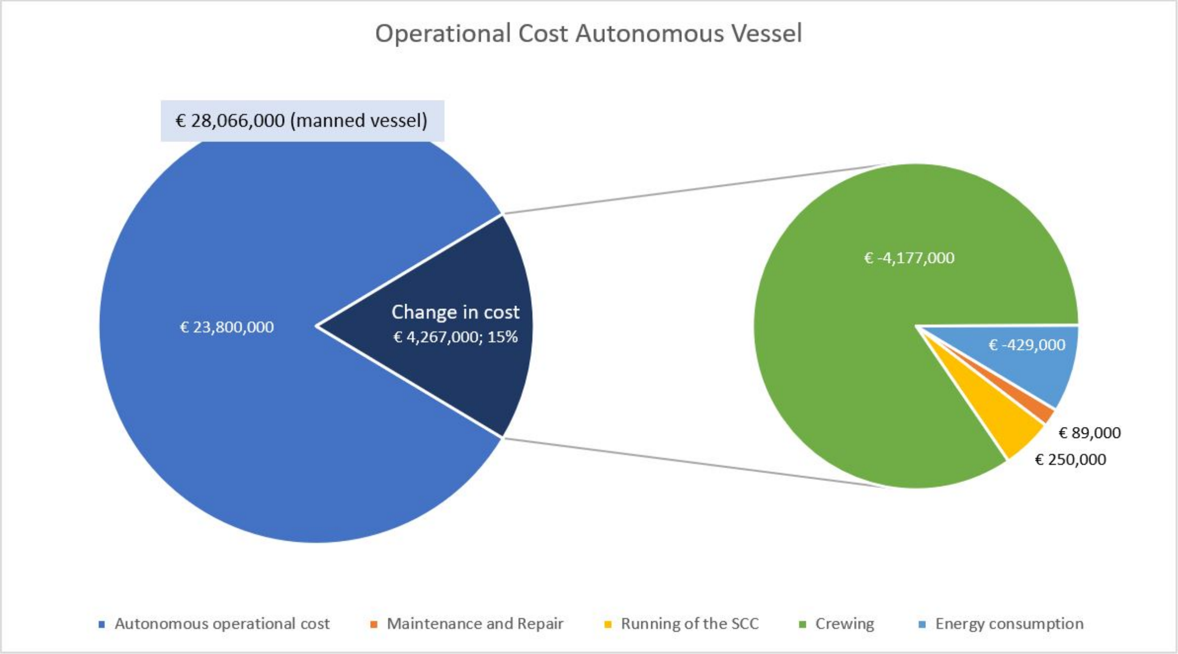

Figure 7.4.3: operational Cost Division Autonomous Dredger

The operational cost are decreased with 15%. This is smaller compared to the first case since the overall operational cost are larger.

In total a cost decrease of € 685,000 + 4,267,000 = € 4,952,000 is obtained over the 25 years lifetime of the dredger. This is a total decrease of 14% compared to the sum of the conventional OPEX and CAPEX.

7.4.3. Effect Operational Conditions

With the obtained results, the effect of the operational conditions are tested. These results are compared to the results from the first case study.

Effect Displacement

In case I it is concluded that a decrease in draft realises a slightly larger cost benefit. For this case an increase in draft realises a slightly larger battery decrease. The result for the original draft and minus and plus 0.5 meters are shown in table 7.4.1.

Table 7.4.1: Draft Variation Benefits case II

T		$\Delta Ec_{battery}$ (kWh)	**Manned cost**	**Autonomous cost**	Δ_{cost}	% Total Benefit
3 (2.93) m	$C_{batteries}$	-296 kWh	€ 4,386,000	€ 4,285,000	-€ 101,000	
m	$C_{econsumption}$		€ 18,674,000	€ 18,245,000	-€ 429,000	
					- € 530,000	10.7 % *
3.5 (3.43) m	$C_{batteries}$	- 299 kWh	€ 4,556,000	€ 4,455,000	-€ 101,000	
m	$C_{econsumption}$		€ 19,400,000	€ 18,967,000	-€ 433,000	
					- € 534,000	10.8 % **
2.5 (2.43) m	$C_{batteries}$	-294 kWh	€ 4,205,000	€ 4,105,000	-€ 100,000	
m	$C_{econsumption}$		€ 17,906,000	€ 17,481,000	-€ 425,000	
					- € 525,000	10.6 % ***

* Based on the maximum benefit of € 4.95 million; ** € 4.96 million; *** € 4.95 million

In case I it was concluded that an originally smaller displacement resulted in a positive effect on cost. For this vessel this statement is not true. The absolute and percentage benefit is largest for the vessel with largest draft. The differences however, are negligible.

Effect Battery Capacity

Both the effect of the hotel load, ship speed and ship range are considered in this section.

Hotel Load
The manned vessel has a power requirement for the hotel systems of 10 kW on average. The case for an average value of 14 kW is shown in table 7.4.3.

Table 7.4.3: Battery Capacity Variation Benefits Case II

	Average Hotelload	$\Delta Ec_{battery}$	**Manned Cost**	**Autonomous cost**	Δ_{cost}	% Total benefit
$C_{batteries}$	10 kW	-296 kWh	€ 4,386,000	€ 4,285,000	-€ 101,000	
$C_{econsumption}$	10 kW		€ 18,674,000	€ 18,245,000	-€ 429,000	
					- € 529,000	11% *
$C_{batteries}$	14 kW	-377 kWh	€ 4,273,000	€ 4,145,000	-€ 128,000	
$C_{econsumption}$	14 kW		€ 18,196,000	€ 17,651,000	-€ 545,000	
					-€ 673,000	13% **

* Based on the maximum benefit of € 4.9 million ** Based on the maximum benefit of € 5,1 million

An additional benefit of € 144,000 is obtained. Also the percentage cost benefit is larger for the vessel with larger hotel load. This is also concluded in the first case.

Ship Speed and Range
The battery capacity of the current vessel is quite large. The cost for the purchase of batteries for this vessel 62 % of the total capital cost. Therefore the situation is considered were only 6 hours of dredging is done instead of 8 hours per trip. The result in cost for the batteries and energy consumption is shown in table 7.4.5.

Table 7.4.5: Battery Capacity Variation Benefits

	E_c Conventional	$\Delta Ec_{battery}$	**Manned Cost**	**Autonomous cost**	Δ_{cost}	% Total benefit
$C_{batteries}$	12912 kWh	-296 kWh	€ 4,386,000	€ 4,285,000	-€ 101,000	
$C_{econsumption}$	12912 kWh		€ 18,674,000	€ 18,245,000	-€ 429,000	
					- € 529,000	11% *
$C_{batteries}$	10600 kWh	- 264 kWh	€ 3,600,000	€ 3,510,000	-€ 90,000	
$C_{econsumption}$	10600 kWh		€ 15,330,000	€ 14,948,000	-€ 382,000	
					-€ 472,000	10%

* Based on the maximum benefit of € 4.9 million ** Based on the maximum benefit of € 4.89 million

As shown in the last two columns of the table, the absolute and percentage cost decrease is largest for the vessel with the originally larger battery capacity. The same conclusion is drawn for the first case.

Effect Distance to Shore

Two satellite receivers are necessary for this vessel. The cost for the additional communication receivers are € 185,000. This addition causes a cost reduction which is 4% smaller compared to the same vessel sailing within Wi-Fi range.

Effect Vessels Operation

For larger vessels the number of crew increases. For this vessel it is straight forward that an increase in conventional crew realises a larger reduction if these members are replaced by software. Compared to case I the contribution of the crew cost on the operational cost is smaller. The energy cost is more significant for this case. The yearly salary for which the operational cost are equal for the manned and autonomous vessel is € 34,000. In table 7.4.7 the comparison on crewing cost compared to the total operational cost is shown.

Table 7.4.7: Crew Size Reduction Effects

	Manning Cost	Total OPEX	% Manning Cost	OPEX Benefit
Master, chief engineer, chief officer, boatswain	€ 5,427,000	€ 28,066,000	19%	- € 4,267,000
Master, chief engineer	€ 3,564,000	€ 24,841,000	14%	- € 2,434,000
Master, boatswain	€ 2,510,000	€ 23,018,000	11%	- € 1,397,000
2 x boatswain	€ 1,290,000	€ 20,906,000	6%	- € 197,000
Crew member(s) X	€ 1,089,000	€ 20,559,000	5%	0

As shown in the table the percentage of the reduced manning cost to the total operational cost is smaller compared to case I.

Smaller Accommodation
If the vessel has an accommodation of 35 tonnes instead of 58 tonnes the overall cost would decrease. The results in battery, energy and accommodation cost are shown in table 7.4.8.

Table 7.4.8: Capital Cost changes

System	**Benefit for 58 tonnes**	**Benefit for 35 tonnes**
Batteries cost	-€ 101,000	-€ 89,000
Accommodation and equipment	-€ 1,022,000	-€ 699,000
Cost energy consumption	-€ 429,000	-€ 377,000
Total	€ 1,551,000 31% (of € 4,952,000)	€ 1,165,000 26% (of € 4,566,000)

It is concluded that a smaller cost reduction is obtained for a smaller accommodation. The percentage cost decrease for the accommodation of 58 tonnes is larger (31%) compared to the 35 tonnes accommodation (26%). The same conclusion is drawn for case I.

7.5. Conclusions and Recommendations on Case Studies

For both cases a cost reduction is realised for the autonomous vessel variant. The capital cost reduction is mostly related to the removal of the accommodation and equipment. The operational cost reduction for crewing in the first case is more significant compared to the second case. As shown in table 7.5.1, the second case realises a larger absolute cost reduction. The first case on the other hand, realises a larger percentage cost reduction.

Table 7.5.1: Overview capital and operational cost for case I and II

		Manned Vessel	Autonomous Vessel	Decrease in Cost	% Total
Case I	Capital Cost	€ 5,000,000	€4,495,000	€ 505,000	-10%
Case I	Operational Cost	€ 10,452,000	€ 7,088,000	€ 3,364,000	-32%
Case I	Total	€ 15,452,000	€ 11,583,000	€ 3,868,000	**-25%**
Case II	Capital Cost	€ 7,000,000	€ 6,315,000	€ 685,000	-10%
Case II	Operational Cost	€ 28,066,000	€ 23,800,000	€ 4,266,000	-15 %
Case II	Total	€ 35,066,000	€ 30,115,000	€ 4,951,000	**-14%**

In the second case the total operational cost are significantly higher due to the high energy consumption and price. The removal of the crew has therefore in percentage more effect on the total operational cost decrease.

Furthermore, an answer to sub-question 9 is presented:
What operational conditions affect the operation of an autonomous vessel most regarding economic viability? And to what extent?

It is concluded that the displacement, battery capacity, distance to shore and the vessels specific operation affect the economic viability. For both cases it is concluded that:

- The absolute and percentage cost decrease is largest for vessels with originally larger battery capacity
- Absolute and percentage, the largest cost decrease is realised for vessels sailing close to shore
- The absolute and percentage cost decrease is largest for vessels with an originally larger accommodation
- The crew cost can be reduced significantly to obtain the situation were no operational cost reduction is realised.

7.5.1. Discussion on Cost Parameters

The conclusions in this chapter are based on certain cost parameters. These are found in the available literature. In this section it will be checked whether the conclusions on the operational conditions are still valid if several parameters change.

For some of the cost parameters the price might be different, which result in a new cost situation. The absolute benefit in capital or operational cost will change.

At first the possible changes in capital and operational cost parameters are presented, where after the conclusions on the operational conditions are discussed.

Capital Cost

For the first case the reduction in capital cost is € 505,000, or € 497,000 for a different battery price. The largest additions in cost are the ICT and mooring, and the largest decrease is caused by the size of the accommodation

ICT and mooring:
The estimation for ICT cost and the cost for the mooring system might be larger, but not more than € 505,000. Even if the ICT and mooring cost (€ 200,000) are increased with 300%, a capital cost reduction is realised. This is also valid for the second case.

Size accommodation:
The size of the accommodation has a large influence on the cost reduction. However, even if the equipment, steel and joinery are halved in price, a cost reduction in realised.

In conclusion, the cost parameters can be changed significantly, but still provide an overall cost reduction.

Operational Cost

In case an energy price of 0.05 €/kWh is applied instead of 0.17 €/kWh, the benefit in energy consumption will decrease. The manning cost however, has a more significant effect on the total operational cost decrease. For both cases it is concluded that reduction in crewing cost still realises an operational cost reduction. For the first case this is 30% of the total operational cost for the manned vessel. For the second case the manning cost are 5% of the total operational cost. It is shown that even in a situation were the crewing cost are lower, there is still a cost reduction.

The change in cost parameters also effect the conclusions on operational conditions;

Operational Conditions

Both the absolute cost and percentage of the total benefit change for different cost parameters. In this section it is demonstrated that the conclusions drawn in the previous section are still valid. The size of the reduction and its percentage effect however, changes.

A case is considered were the cost for ICT and mooring are increased with 200%. In addition, the crewing cost are halved. The total cost reduction for case I decreases with $1 - \frac{1{,}317{,}000}{3{,}869{,}000} = 65\%$. This causes a situation where an overall lower cost reduction is realised. The situation is shown for one of the operational conditions, the displacement. In table 7.5.2 the results are shown if a different price for manning, ICT and mooring are used. It is proved that the percentage decrease changes, but the effect remains the same.

Table 7.5.2: Draft Variation Benefits

	T		$\Delta Ec_{battery}$	Max reduction	Δ_{cost}	% Total benefit
Original	1 (0.9) m	$C_{batteries}$	-111 kWh	€ 3,869,000	**- € 198,000**	5.1%
	1.5 (1.4) m	$C_{batteries}$	-109 kWh	€ 3,864,000	**- € 195,000**	5.0%
	0.5 (0.4) m	$C_{batteries}$	-117 kWh	€ 3,880,000	**-€ 211,000**	5.4%
New	1 (0.9) m	$C_{batteries}$	-111 kWh	€ 1,317,000	**- € 198,000**	15.1%
	1.5 (1.4) m	$C_{batteries}$	-109 kWh	€ 1,313,000	**- € 195,000**	14.8%
	0.5 (0.4) m	$C_{batteries}$	-117 kWh	€ 1,328,000	**- € 211,000**	15.9%

8

Conclusions Research

In this research the motivation and challenges of autonomous shipping are presented. It is concluded that the systems for autonomous shipping are available, but the software must be improved. In addition, some obstacles consist regarding regulation and ethics. Furthermore, autonomous vessels must be at least as safe as conventional manned vessels to be accepted.

With regard to reliability, it is concluded that electric propulsion ensures a higher level over diesel propulsion. It is also concluded that an autonomous operation increases the operational efficiency of a vessel.

The results from thesis can be used by researchers and ship owners to determine whether a ship design and its operation are economically viable. This is valuable for investors to decide whether their case is favourable for autonomous shipping. The main question answered in this thesis is:

What are the operational conditions under which an autonomous battery powered vessel design is economically viable over its electric manned variant?

To answer the main question, seven supporting questions have been presented. The answers of these questions work towards an answer to the main question. The answer to the main question is found in the output of the developed design and cost analysis tool. This tool is developed with the help of the sub-questions of which a summary is presented here.

1. What is the operational range under which electric propulsion is favourable over diesel engine driven vessels?
This research focuses on fully electric propulsion. As discussed in chapter 3, a disadvantage of batteries is the high weight and cost. It is concluded that at this moment in time electric propulsion is only favourable for very small operational ranges with low power requirements. For the Lady Anna, the vessel used in the comparison, an electric propulsion system and its equipment are heavier above capacities of 80 kWh. For this vessel that capacity is reached within an hour of sailing. Furthermore, the volume is dependent on the size of the engine room, but the size of the batteries is increasing with a factor 1.3 to 3.7 $\cdot h_{sailing}$, where the HFO increases with 0.24 $\cdot h_{sailing}$. Over 10 hours this results in a difference of 10 to 34 m^3 difference. For the cost the intersection point is located between 1.5 and 3 hours sailing, dependent on the battery price. In conclusion, despite some rough assumptions, it is made clear that electric propulsion is not favourable over diesel for most cases. The reduction in green house gases can however outweigh the weight, volume and cost disadvantages.

2. To enable the transition from a battery powered manned vessel design to a battery powered unmanned design, what systems and requirements are added/removed?
As discussed in chapter 4, the autonomous vessel design differs from the manned design. Crew related equipment is removed, software and some systems to increase the reliability are added. These changes lead to a change in weight and power requirement.

The additions in weight for mooring arms and additional fire protective walls become irrelevant compared to the removed weight for the accommodation steel, joinery and equipment. The size of the accommodation has therefore a significant contribution to the change in total weight. The power requirement for the robot arms, communication system and navigation system are relatively small compared to the removed hotel load and HVAC power requirement. In conclusion, the removals in weight and power are larger compared to the additions, which results in a consequence on ship design, as discussed in chapter 5.

3. What effect do the additional systems and design requirements have on the total ship design? How big are these effects?
The design changes result in several consequences on the total ship design. Not all steps of the design spiral are considered, the largest factors are included and discussed. The changes in lightweight, displacement, draft, trim and power are presented. The equations are shown in chapter 5.

A reduction in weight reduces the total lightweight as well. The reduction in lightweight results in a decrease in displacement, which decreases the draft as well. For vessels with a conventional accommodation, a shift in trim is expected. This shift is dependent on the weight and the distance to the center of flotation. Dependent on the total displacement of the vessel this trim must be considered in the optimising phase of the design.

4. How does autonomy change the operational performance of electric vessels?
It is concluded that a decrease in draft realises a lower required brake power. In addition to the decrease in total power requirement for other systems, a decrease in energy consumption is realised. The operational efficiency thus increases.

Furthermore, the change in operational efficiency changes the operational range under which electric propulsion is favourable over diesel propulsion. A weight and volume comparison is given for the example vessel, the Lady Anna. It is concluded that the effect of autonomous shipping increases over the sailing hours, but does not significantly increase the range under which electric propulsion is favourable over diesel propulsion. It is however clear that the absolute reduction in weight, volume and cost is largest for the largest displacement decrease.

5. What are the (operational and capital) cost that arise from removing the crew of board? &
6. What are the (operational and capital) savings of a battery powered autonomous vessel in comparison with the manned battery powered variant?
The change in ship design and operation result in a change in capital and operational cost. Both additional cost and savings are presented in chapter 6.

For the Lady Anna the most significant reduction in cost is caused by the removal of the accommodation and its equipment. For the Lady Anna this is approximately € 700,000. The increase in capital cost is caused by the additional systems for communication, navigation, fire-protection, mooring and ICT. It is expected that these additions are smaller compared to the decrease in cost for the accommodation. Overall a decrease in capital cost is expected, but as shown, this is highly dependent on the size of the accommodation and its equipment.

The operational cost are characterized by the decrease in cost for manning, and the increase in cost for the running of the SCC. In addition, the more efficient operation realises a lower energy consumption. It is concluded that the manning cost has a large influence on the total operational cost reduction.

7. What operational conditions affect the operation of an autonomous vessel most regarding economic viability? And to what extent?
This question is answered with the help of a case study. In this case study an electric dredger operating in a port is considered. With the help of the tool the changes in design and cost between the manned and the autonomous vessel are obtained. The cost parameters are considered after which it is concluded that four operational conditions effect the economic viability most. The operational conditions are:
· Displacement · Battery capacity · Distance to shore · Vessel specific operation

The tool developed in this research is generally applicable for several types of vessels. Two case studies are performed, a summary of their results is presented here.

8.1. Conclusions on Case Studies

Two case studies are performed. The second case study presents a vessel which is slightly larger with a larger operational range. For both vessels a reduction in capital and operational cost is realised. The cost decrease over the 25 years lifetime of the vessels is shown in table 8.1.1.

Table 8.1.1: Overview capital and operational cost for case I and II

		Manned Vessel	Autonomous Vessel	Decrease in Cost	% Total
Case I	Capital Cost	€ 5,000,000	€4,495,000	€ 505,000	-10%
Case I	Operational Cost	€ 10,452,000	€ 7,088,000	€ 3,364,000	-32%
Case I	Total	€ 15,452,000	€ 11,583,000	€ 3,868,000	**-25%**
Case II	Capital Cost	€ 7,000,000	€ 6,315,000	€ 685,000	-10%
Case II	Operational Cost	€ 28,066,000	€ 23,800,000	€ 4,266,000	-15 %
Case II	Total	€ 35,066,000	€ 30,115,000	€ 4,951,000	**-14%**

8.2. Conclusions on Operational Conditions

With the output from two case studies, recommendations are done on the operational conditions. The conclusions on these operational conditions answer the main research question. It is concluded that:

- The battery capacity of the manned vessel has influence on the total benefit for the autonomous variant. It is concluded that the larger the original battery capacity, the larger the absolute and percentage cost reduction for the autonomous vessel variant. The size of the reduction is case dependent.
- For vessels sailing close to shore, within WiFi range, the total cost reduction is largest. For vessels sailing outside the WiFi range, additional expenses for the communication systems must be paid. An additional € 185,000 is spend. This is significant compared to the total decrease in cost for both cases (€ 505,000 and € 685,000).
- The vessels specific operation determines the size of the crew and the accommodation. Both factors have a significant influence. The size and salary of the crew influence the operational cost reduction significantly. For vessels with larger operational cost, the percentage manning cost reduces, but the absolute reduction is still large. The size of the accommodation influences the weight and cost reduction. It has therefore effect on the cost reduction, but also on the change in energy consumption and battery capacity. For larger accommodations the absolute and percentage cost reduction is largest.
- A more efficient operation is realised for the autonomous variant of a vessel. This is valid for the condition that a weight and draft reduction are realised. The displacement of the manned vessel influences the cost reduction for the autonomous vessel. The conclusions on displacement for the cases are contradictory. In chapter 9 it is therefore suggested to extend the study on displacement.

With the conclusions drawn it is favourable to invest in the autonomous variant of a manned vessel which:

- Has a large hotel load. This results in a decrease in battery capacity and energy consumption.
- Requires a large battery capacity for the operation. For a similar operation, the largest cost decrease is realised for vessels with an originally larger battery capacity. Hereby it is favourable if the propulsion and hotel power are most significant, since the largest reductions are realised for those parameters.
- Has a large accommodation. The larger the accommodation, the larger the cost and weight decrease, which causes the largest cost reduction for the autonomous variant.
- Has high crewing cost. Under the assumption that all crew tasks are replaced by systems, the absolute operational cost decrease is largest for vessels with high crewing cost.
- Is sailing close to shore, within the Wi-Fi zone. This decreases the cost for the communication system.

9

Recommendations

In this chapter suggestions for further research are presented. These suggestions are based on the assumptions made in this research and literature. Suggestions on ship design and the cost analysis are given.

Starting with the recommendations for the ship design:

- Improve the weight and power estimations for the accommodation. In this research it is concluded that the weight and size of the accommodation have a significant influence on the cost of the manned vessel. A research on accommodation sizes per type of vessel and operation could support the conclusions of this research.
- Add more ship type dependent additions. Autonomous dredging equipment, autonomous crane handling or autonomous ballast solution could be explored further to make this research broader applicable.

Secondly the recommendations for the cost model are given:

- Specify the cost related to mooring and ICT. The cost used in this research are rough estimations since little information is available. More specified cost could lead to a more detailed analysis on the operational conditions.
- Include the cost related to autonomous regulation. A study could be performed on the additional measures and related cost. Currently, these cost are not included.
- Include insurance cost. Currently, the cost for the autonomous vessel are assumed constant for insurance. Insurance companies might be reluctant to invest in autonomous shipping. This might increase their prices.
- Explore autonomous dredging technologies. In this research no attention is paid to autonomous dredging technologies. The current power requirements are assumed constant for the manned and autonomous vessel. Since the total dredging power has a significant influence on the total energy consumption it is worth looking in the consequences on cost, weight and power of autonomous dredging equipment.
- The effect on displacement for the cases I and II differs. Both studies provide a different conclusion on the favourability of a smaller or larger draft. It is recommended to extend this study to find under what circumstances the displacement has which effect.

A

Trendlines Wärtsila Engines

Trendlines to compare weight and volume over the engine power.

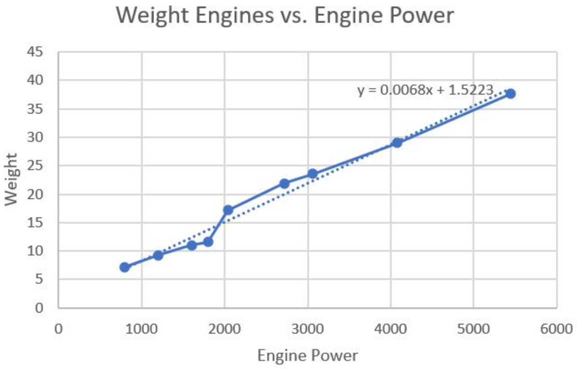

Figure A.0.1: Trendline Engines on Weight [101]

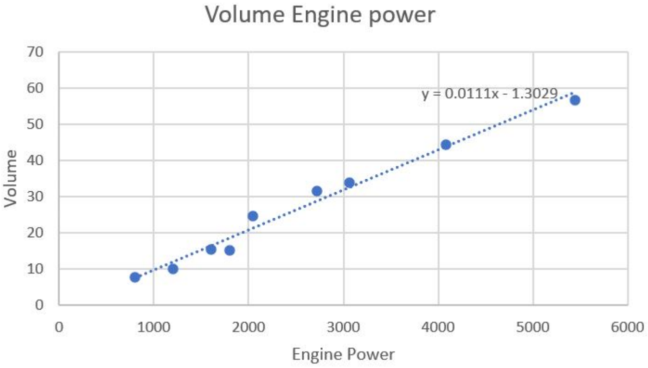

Figure A.0.2: Trendline Engines on Volume [101]

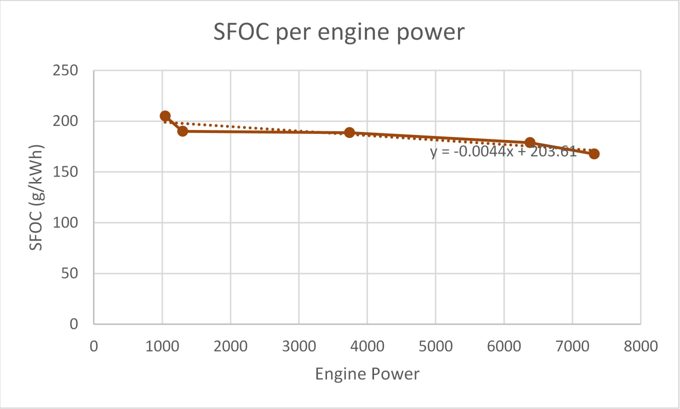

Figure A.0.3: Trendline Engines and its SFOC in g/kWh

Table A.0.1: Engines and their SFOC [101]

Engine type	Engine Power Range (kW)	SFOC (g/kWh)
L20	800-1800	190.0
L26	2040-5440	188.7
W14	749-1340	205
W31	4880-9760	167.7
L31/V32	3480-9280	178.8

B

Trendlines Electric Motors

Trendlines to compare weight and volume over engine power of an electric motor [36].

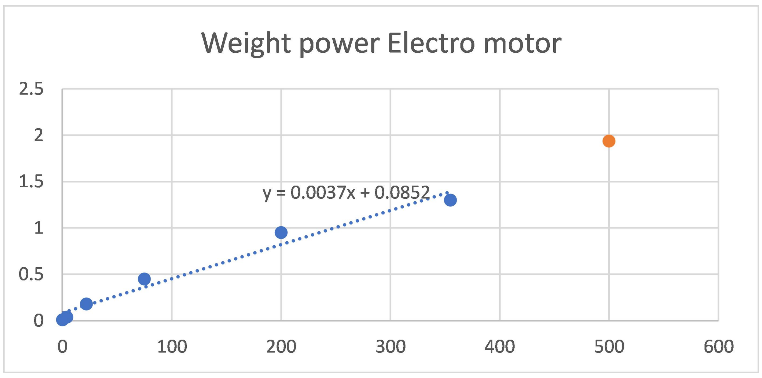

Figure B.0.1: Weight electric motor trendline for small and big engines [36]

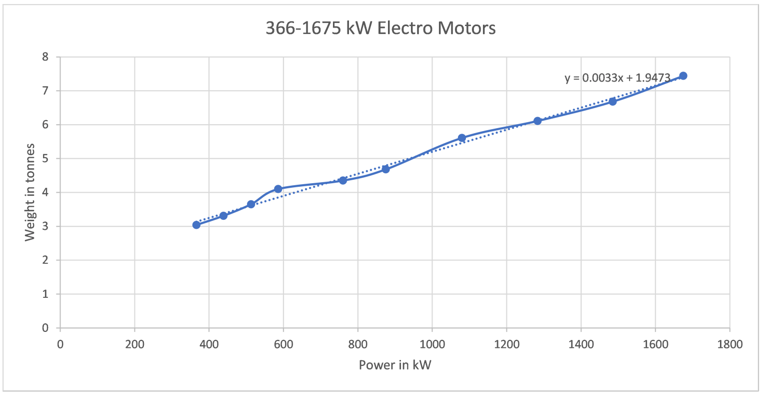

Figure B.0.2: Weight electric motor trendline for small and big engines [36]

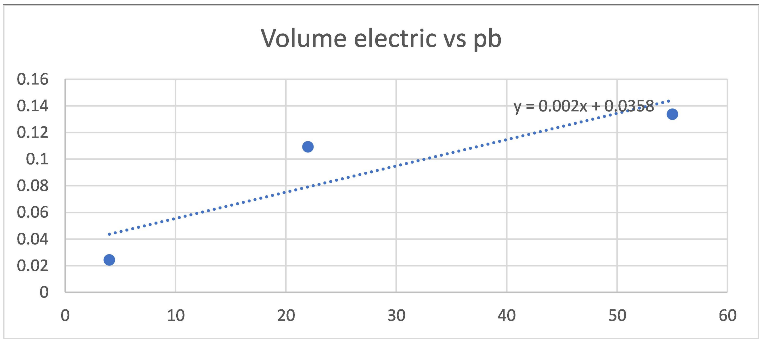

Figure B.0.3: Volume electric motors trendlines [36]

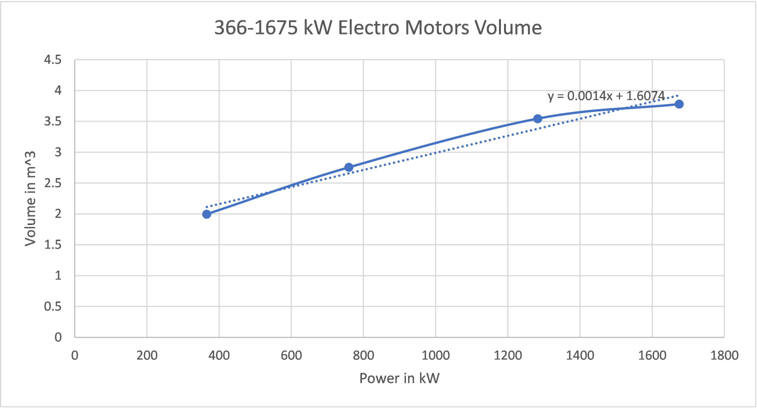

Figure B.0.4: Volume electric motor trendline [36]

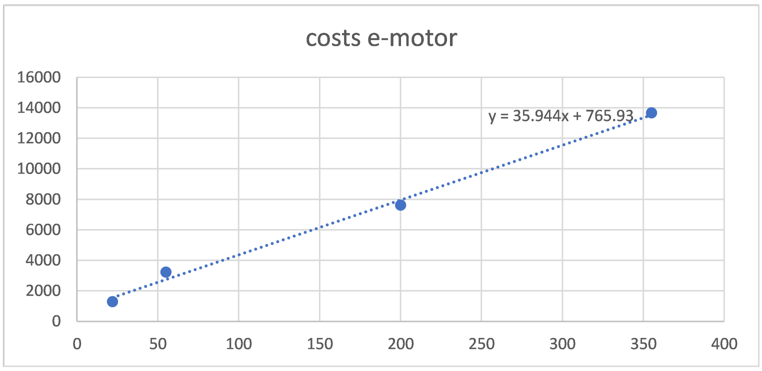

Figure B.0.5: Cost electric motor trendline [36]

C

Matlab Codes

C.1. Weight Comparison

```
clc
clear all
close all

Pb = 749; % kW

C1 = (0.55*749)/((10*0.5114)^3); % kW
Vs = 0.5114*10; % knts
Pe = C1 * Vs^3; % kW
h_sailing = [0:0.1:10] ;
We = h_sailing*Pe

%Diesel
SFC = -0.044*Pb + 203.61 ; %g/kWh
eta_e = 3600000/(40500*SFC);
P_consumptiondiesel = Pe / (0.55*eta_e);

W_engine = 0.0068*Pb+1.5233;
W_fuel = P_consumptiondiesel*h_sailing*SFC*10^(-6)

Wtotaldiesel = W_engine + W_fuel

% Electric
P_consumptionelectric = Pe / (0.55*0.85);

% W_motor = 0.0033*Pb+1.9473 ;
W_motor = 0.0037*Pb+0.0852
% W_motor = 0.0033*Pb + 1.9473
W_batteries = P_consumptionelectric*h_sailing/220 ;
Wtotalelectric = 2*W_motor + W_batteries

% Plot work work (plot We and We_e), hours (plot h_sailing)
plot(We,Wtotaldiesel,'r')
hold on
plot(We,Wtotalelectric,'b')
xlabel('Work [kWh]')
```

```
ylabel('Weight Total Propulsion [tonnes]')
[~,h_legend]= legend('Diesel Propulsion','Electric Propulsion');
```

C.2. Fuel and Batteries Comparison

```
Pb = 749; % kW
C1 = (0.55*749)/((10*0.5114)^3); % kW
Vs = 0.5114*10; % knts
Pe = C1 * Vs^3; % kW
h_sailing = [0:0.1:10] ;
We = h_sailing*Pe

%Diesel
SFC = -0.044*Pb + 203.61 ; %g/kWh
eta_e = 3600000/(40500*SFC);
P_consumptiondiesel = Pe / (0.55*eta_e);

W_engine = 0.0068*Pb+1.5233;
W_fuel = P_consumptiondiesel*h_sailing*SFC*10^(-6)

Wtotaldiesel = W_engine + W_fuel

V_fuel = W_fuel/1.010 %m^3

% Electric
P_consumptionelectric = Pe / (0.55*0.85);
% W_motor = 0.0033*Pb+1.9473 ;
W_motor = 0.0037*Pb+0.0852
W_batteries = P_consumptionelectric*h_sailing/220 ;
Wtotalelectric = 2*W_motor + W_batteries

V_batteries1 = P_consumptionelectric * h_sailing/240;
V_batteries2 = P_consumptionelectric * h_sailing/500;
V_batteries3 = P_consumptionelectric * h_sailing/690;
% Plot work work (plot We and We_e), hours (plot h_sailing)
plot(h_sailing,V_fuel,'r')
hold on
plot(h_sailing,V_batteries1,'b')
hold on
plot(h_sailing,V_batteries2,'g')
hold on
plot(h_sailing,V_batteries3,'c')
xlabel('Sailing hours [h]')
ylabel('Volume HFO vs. Batteries [m^3]')
[~,h_legend]= legend('HFO','240 kWh/m^3 Batteries','500 kWh/m^3 Batteries','690 kWh/m^3 Batteries
```

C.3. Cost Comparison

```
Pb = 749; % kW
C1 = (0.55*749)/((10*0.5114)^3); % kW
Vs = 0.5114*10; % knts
Pe = C1 * Vs^3; % kW
h_sailing = [0:0.1:10] ;
We = h_sailing*Pe
```

```
%Diesel
SFC = -0.044*Pb + 203.61 ; %g/kWh
eta_e = 3600000/(40500*SFC);
P_consumptiondiesel = Pe / (0.55*eta_e);

W_engine = 0.0068*Pb+1.5233;
W_fuel = P_consumptiondiesel*h_sailing*SFC*10^(-6)

Wtotaldiesel = W_engine + W_fuel

V_fuel = W_fuel/1.010 %m^3

C_engine = 1322*Pb^(0.79);
C_fuel = 415.3*P_consumptiondiesel*h_sailing*SFC*10^(-6);
C_diesel = (1.25*C_engine + C_fuel)/(10^6) ;



% Electric
P_consumptionelectric = Pe / (0.55*0.85);
% W_motor = 0.0033*Pb+1.9473 ;
W_motor = 0.0037*Pb+0.0852
W_batteries = P_consumptionelectric*h_sailing/220 ;
Wtotalelectric = 2*W_motor + W_batteries

V_batteries1 = P_consumptionelectric * h_sailing/240;
V_batteries2 = P_consumptionelectric * h_sailing/500;
V_batteries3 = P_consumptionelectric * h_sailing/690;
% Plot work work (plot We and We_e), hours (plot h_sailing)

C_emotor= 100*Pb ;
C_batteries = 113 * P_consumptionelectric*h_sailing;
C_batteries2 = 55* P_consumptionelectric*h_sailing;
C_batteries3 = 110 * P_consumptionelectric*h_sailing;
C_energy = 0.05*P_consumptionelectric*h_sailing;
C_equipment = 0.25*C_emotor;

Celectric1 = (2*C_emotor + C_batteries + C_energy + C_equipment)/(10^6) ;
Celectric2 = (2*C_emotor + C_batteries2 + C_energy + C_equipment)/(10^6) ;
Celectric3 = (2*C_emotor + C_batteries3 + C_energy + C_equipment)/(10^6) ;

plot(h_sailing,C_diesel,’r’)
hold on
plot(h_sailing,Celectric1,’b’)
hold on
plot(h_sailing,Celectric3,’g’)
hold on
plot(h_sailing,Celectric2,’c’)

xlabel(’Sailing hours [h]’)
ylabel(’Cost Diesel and Electric Propulsion [m€]’)
[~,h_legend]= legend(’Diesel propulsion’, ’Electric propulsion 113$/kWh’,’Electric propulsion 110$/kWh’
```

D

Explanation Navigation Terms

RMU (*Motion Reference Units*)	This sensor can measure ship motions like roll and pitch, accelerations, angular rates and velocity
IMU (*Inertial Measurement Unit*)	This sensor uses the forces measures to determine the attitude, angular rates, linear velocity and position of the ship
AIS (*Automatic Identification System*)	With AIS data ships can view position and characteristics of surrounding traffic using VHF transceiver and receiver.
Daylight/Infrared camera	Instruments to build maritime picture displaying image pixels. It detects objects and their global position. Infrared uses laser to detect objects in the darker circumstances.
Compass	Instrument for determining position and direction ship relative to Earth's magnetic poles.
Radar *(Radio detection and Ranging*)	Detection system that uses radio waves for detection of range, angle or velocity of objects.
LiDAR (*Light Detection and Ranging*)	This remote sensing method uses laser pulses to measure ranges.
GNSS (*Global Navigation Satellite System*)	This system uses satellites to help with situational awareness.
ECDIS (*Electronic Chart Display Information System*)	This system displays the sea routes according to IMO standards. The route of a vessel can be determined with this information.

E

Characteristics Case II

Table E.0.1: Operation Characteristics Recirculation Dredger Case II

Hours	Operation	Speed & Corresponding Installed Power	Pump Power (dredging)	Mooring Power	Average Hotelload	Consumed Power	Total Work needed
3 hrs	Sailing	10 knots, 713 kW	0	0	0	839 kW	2516 kWh
12 hrs	Hotel	2 knots, 0 kW	0	0	10 kW	11.7 kW	141 kWh
8 hrs	Dredging	2 knots, 78 kW	600 kW	0	0	797 kW	6379 kWh
1 hrs	Mooring	0 knots, 0 kW	0	2 kW	0	2 kW	2 kWh
12 hrs	All						12912 (9039) kWh

Table E.0.2: Operation Characteristics **Autonomous** Recirculation Dredger Case II

Hours	Operation	Speed & Corresponding Installed Power	Pump Power (dredging)	Mooring Power	Average Hotelload	Consumed Power	Total Work needed
3 hrs	Sailing	10 knots, 689 kW	0	0	0	811 kW	2433 kWh
12 hrs	Hotel	2 knots, 0 kW	0	0	1.35 kW	1.59 kW	19 kWh
8 hrs	Dredging	2 knots, 77 kW	600 kW	0	0	796 kW	6368 kWh
1 hrs	Mooring	0 knots, 0 kW	0	10 kW	0	10 kW	10 kWh
12 hrs	All						12615 (8831) kWh

E.1. Output Characteristics

Table E.1.1: Results weight, power, energy, layout from Tool

System	Weight (tonnes)	Maximum Power (kW)	Layout
Navigational additions	-	36.25[*]	radars, camera and soundreceivers on deck
Communicational additions	-	1.35	Wi-Fi receiver on deck
Additional reliability and fire protection battery packs	0.48	0	2 m^3 additional battery rooms space
Accommodation	- 58.5	- 43.7	accommodation removed
Mooring arms	11 [4 arms]	10	on deck 4 sides
Several (hotel) Equipment	-14.6	-12	mostly in accommodation
Totals	**-61.62**	**- 44.35**	

[*] Navigational additions are back-up systems. It therefore has no effect on the peak power and energy consumption of the vessel.

Table E.1.3: Ship Characteristics

	L	**B**	**T**	Δ	v_s **dredging**
Manned	72 m	14 m	3 m	2510 tonnes	2 knots
Autonomous	72 m	14 m	2.93 m	2452 tonnes	2 knots
Δ			-0.07 m	- 58 tonnes	

Table E.1.4: Weight and position systems dredger

System	**Weight (tonnes)**	**Position (m)**	**Moment** $m \cdot s$
Additional firewalls/batteries	4.1 tonnes	-5 m (C.o.F.)	- 20.7 m · tonnes
Decrease battery size	-1.4 tonnes	-5 m	7 m · tonnes
Accommodation steel and joinery	58.5 tonnes	-18m	-1054 m · tonnes
Equipment Accommodation	14.6 tonnes	-18 m	-263 m · tonnes
Mooring arms	11 tonnes [total]	+/- 18 m (ps/sb)	0

$$\alpha_{dredger} = \arctan \frac{m \cdot s \cdot g}{\rho_w \cdot g \cdot \nabla_{new} \cdot GM_L} = -0.01 rad = -0.39 \quad [degrees] \tag{E.1}$$

F

Hotelload Variation

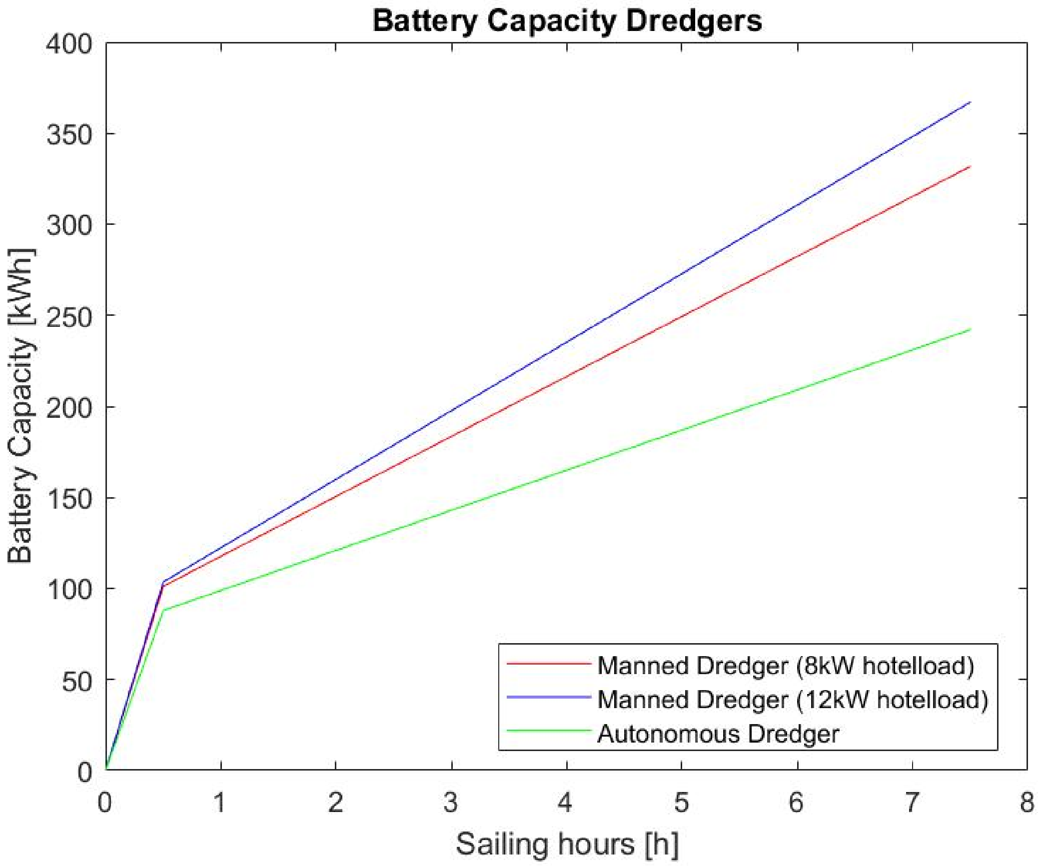

Figure F.0.1: Visual - Hotelload Variation for Case I

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