The suitability of placing batteries near the hull sides from a collision and safety perspective

Based on statistics and simulation data

Bachelor thesis for Marine Engineering Programme

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Preface

This report was written during the spring of 2024 as a Bachelor thesis of the Marine Engineering program at Chalmers University of Technology.

The idea for this report sprung out of the rapid development of electrical vehicles and ships, and from being informed about battery fires during some parts of the education. As the World tries to phase out fossil fuels, alternative propulsion methods such as battery electric propulsion is on the rise, and with it comes certain challenges that need to be faced, including appropriate infrastructure, operational range, and safety. Hearing and learning about maritime accidents over the years has made it clear that the forces involved in such scenarios can lead to catastrophic damages to the ship and its cargo, and that precautions must be in place to limit the damage extent as much as possible. Batteries are quite fragile by nature, and abusing them can to short circuits, thermal runaway, and fires that are difficult to extinguish. Because of this, it is important to protect the batteries from external damage, and to try to determine were to store the batteries to ensure this.

We would like to thank Per Mottram Hogström at Chalmers University of Technology for being our supervisor during this project, and fellow students at Chalmers for their input at the seminars, and the teachers for their enthusiasm in their work. We would also like to thank our classmates for the four years of higher education that we have faced together, and we hope that we will see each other out on the ocean waves someday.

Johanna Perryd Mattsson & Magne Pedersen, 2024

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SAMMANDRAG

Ambitionen att minska globala utsläpp av växthusgaser är större och starkare än någonsin, och alla branscher måste göra sin del för att det målet ska kunna nås. Sjöfartsindustrin är en självklar del av detta, eftersom en stor del av jordens internationella transporter sker med hjälp av fartyg. Det finns många idéer och potentiella lösningar på hur utsläppen av koldioxid från branschen kan minskas, och det finns en stor fokus på alternativa drivmedel. Att låta fartyg drivas av batterier är ett alternativ som utvecklas mer och mer, men den lösningen kommer med sina begränsningar, som framför allt gestaltar sig i räckvidd och infrastruktur för att ladda batterierna.

För att öka den möjliga räckvidden på fartyget kan det vara lockande att nyttja vartenda ledigt utrymme till förvaring av batterier, men även det kan ha sina nackdelar. Utrymmen som skulle kunna nyttjas till förvaring av batterier är till exempel utrymmen som finns nära bordläggningen, men anledningen till att utrymmen här är tomma eller används till annat ändamål till att börja med är ofta av säkerhets- eller stabilitetsskäl. De utrymmen som är konstruerade ur ett säkerhetsperspektiv finns ofta runt tankar med känsligt innehåll, till exempel kemikalier och olja, som hade kunnat skada miljön om de skulle läcka ut vid en olycka där skrovet skadas.

Batterier är benägna att börja brinna om de skulle kortslutas till följd av deformation, och att då placera batterier i utrymmen som riskerar att utsättas för deformationer vid en kollision kan vara riskfyllt, eftersom en potentiell brand kan leda till ännu större skador på fartyget än vad kollisionsskadorna i sig hade orsakat.

Denna studie försöker svara på om det är lämpligt att placera batterier där de riskerar att träffas vid en kollision med ett annat fartyg, sjöbotten, eller en kaj. Statistik och simulationsdata om batteriers motståndskraft mot deformation, skrovskador, och olycksfördelning har samlats in i en systematisk litteraturstudie och sedan använts för att skapa en riskanalys gällande var batterier bör placeras.

Resultatet visar att battericeller enbart kan komprimeras med ett par millimeter innan cellen fallerar och därav blir risken för brand hög vid en kollision om deformationen skulle nå batterierna.

Nyckelord: Batteridrivna fartyg, kollision, grundstötning, konstruktion, brandsäkerhet, statistik, skrovskador

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ABSTRACT

The ambition to decrease global greenhouse gas emissions is more prevalent than ever, and all industries must do their part to reach that goal. The shipping industry plays a vital role, as a large part of the international transport is being done by ships. There are many ideas and potential solutions on how to reduce the emissions of carbon dioxide from the shipping industry, and those are largely focused on alternative fuel types. Building ships that use batteries as an energy source for propulsion is a concept that is evolving more and more, but it does come with limitations, which are most obvious when it comes to the range of operation and the infrastructure needed to charge those batteries.

To expand the range of operation of the ship it can be tempting to make use of every available space to store batteries, for example spaces close to the side casing or within the double hull, but the reason why the space is empty to begin with, or is used for some other purpose, is often due to the safety or stability of the vessel. The spaces that are constructed from a safety perspective are often found around tanks that can contain sensitive cargo or bunker, like chemicals and oil, which could damage the environment if they were to leak out in case of an accident where the hull would be damaged.

Batteries are prone to catch fire if they are short circuited due to deformation, therefore placing batteries in spaces that can be exposed to deformation in a collision carries a potential risk, since a potential fire can lead to more substantial damage on the ship than what the collision alone would have made.

This study aims to answer if it is appropriate to place batteries where they risk being hit in a collision with another ship, the sea bottom, or a berth. Statistical and simulation data regarding hull damages, accident distribution, and a battery’s resilience against deformation is compiled in a systematic literature review and then used to create a risk analysis on the appropriate placement of batteries.

The results show that battery cells can only be deformed by a few millimetres before the cell fails, meaning that the risk of fire is high in a collision if the deformation would reach the batteries.

Keywords: Battery powered ship, collision, grounding, construction, fire safety, statistics, hull damage

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ACRONYMS AND TERMINOLOGY

EMSA	European Maritime Safety Agency
FSA	Formal Safety Assessment
IACS	International Association of Classification Societies
ILLC	International Convention on Load Lines
IMO	International Maritime Organization
MARPOL	International Convention for the Prevention of Pollution from Ships
RoPax	Roll On and Roll Off cargo combined with Passenger ship
RoRo-cargo	Roll On and Roll Off Cargo
SOLAS	International Convention for the Safety of Life at Sea

1. INTRODUCTION

The global goal of reducing greenhouse gas emissions by removing carbon fuels has led to extensive research and development of the electrical grid and to shift the energy demand from fossil fuels to electricity (Keane, 2023). One of the sectors that is subject to these changes is the transportation sector. The development of electric vehicles has progressed quickly in recent years and electric cars are now available for purchase by most car manufacturers.

Anwar et al (2020) write that the trend of electric transportation also extends to the maritime sector, as the hybridisation of ships has increased. The development of a fully electric maritime industry faces several obstacles of various kinds, for example limited voyage distances, infrastructure for battery charging, and regulations regarding the construction of ships.

According to Liu et al. (2023), one of the most commonly perceived issues with battery electric road vehicles is the operational range, in other words how far the vehicle can drive on one charge. This issue could also translate into the maritime industry, as battery ships also face the problem of limited range. The European Maritime Safety Agency (2023, November 14) has recognised that the low electrical energy density of batteries makes fully electric ships more suited for short-distance voyages and that deep-sea voyages are less suitable.

Liu et al. (2023) found that one way of solving the range anxiety could be to add more or bigger batteries to the vehicle, but that also comes with some concerns, for example decreased efficiency and increased cost. They also state that that more or larger batteries would take up more space in the vehicle, which could also be applicable in the maritime industry.

Trombetta et al (2024) illustrate that while both road vehicles and ships are part of the transportation industry, the order of magnitude regarding the energy needed for the two industries is considerably different. Despite this, the adopted battery technology is usually the same for all parts of the transportation sectors, the maritime industry face particular challenges in the form of weight and space constraints, among others. They also point out that batteries can be a safety hazard if they were to be abused, as it can lead to the battery catching fire and generating toxic gases.

If the method of installing more batteries would be used as way to extend the range of the ship, more batteries would naturally take up more space onboard. They could be placed in areas or spaces that are normally empty or used for something else, as it would be unfavourable to place them in such a way that would decrease the available cargo space. There are some areas that are less suitable for them to placed however, as it could compromise the safety of the vessel. One type of area which could be less suitable for battery placement is close to the hull, in spaces like the double hull compartments. Those areas are most likely to be affected by deformation if a collision would occur, and batteries are prone to catch fire if they are subjected to mechanical abuse.

1.1 Background

The background of this report is the ongoing development of ships with battery propulsion, and how such a propulsion system could possibly alter the way that collision safety is currently handled onboard ships. Trying to use more available space onboard a ship to install more batteries could potentially be dangerous in a collision situation, as damaged batteries can cause a fire.

1.2 Aim of the Study

The aim of this report is to examine the risk of placing batteries in double hull spaces by investigating which parts of a ship that is statistically more likely to receive damage in an accident, what would happen if the batteries were to be deformed in a collision, and then make a risk analysis of which spaces would be more suitable or less suitable to contain batteries from a collision safety perspective.

1.3 Research Questions

The following questions will be addressed:

- What parts of a ship is statistically more likely to sustain damage in an accident?
- Where could batteries be located to reduce the risk of mechanical abuse?
- Can placing batteries in more sensitive spaces to increase the operational range be justified by the risk?

1.4 Delimitations

In this report, there are several different aspects that has not been included as considerations when constructing an electric ship.

Firstly, no considerations have been made for the economical aspect. Batteries are one of the most expensive parts of a fully electric ship, and adding more batteries in the double hull space might not be economically viable.

Secondly, no consideration has been made regarding how the amount or placement of batteries within the double hull could affect the stability characteristics of the ship. Batteries are generally very heavy and dense, so the placement of them could severely impact the stability. It is also worth mentioning that the double hull spaces are often used for ballast tanks, which can be filled and emptied to adjust the stability and the draught of the ship, which would no longer be possible if those spaces were filled with battery packs.

Thirdly, no considerations have been made for how different battery types can be affected differently by deformation and mechanical abuse, this applies to both the material of the electrodes as well as the type of electrolyte used. Only one type of battery will be considered in this report. Furthermore, no consideration has been made regarding the state of charge of the battery and how that could change the effects of mechanical abuse.

Fourthly, no considerations have been made for other conditions that could affect the battery if a collision would occur, for example the effect of water ingress on the battery packs.

2. THEORY

The information found concerning the design of batteries, the conventions and rules that regulate the shipping industry, and the development of electric vehicles and ships will be presented in this chapter. The battery design and its parts will be explained, as well as the procedure used when evaluating risks in a maritime setting.

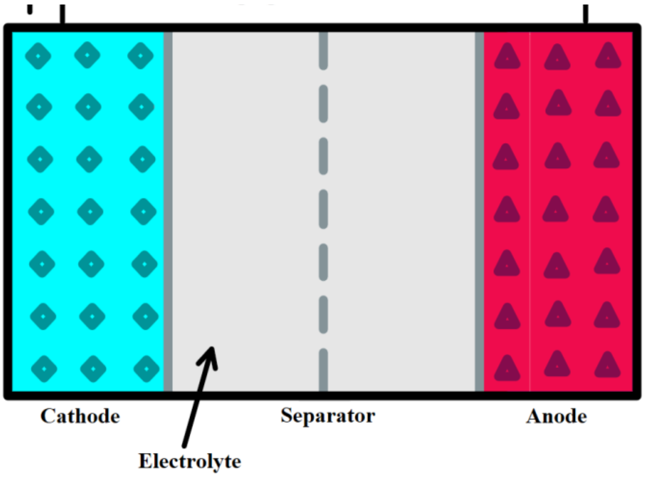
2.1 Battery Design and Safety

The design and safety of batteries plays a large part in how vehicles and portable devices are constructed and designed to ensure the safety of the intended user. The choice of battery type, size, and placement are important factors to consider during the design process, as it affects not only safety, but also the weight, size, and the range or period of operation of the object it is supposed to power.

2.1.1 Battery Design and Components

A Lithium-ion battery cell consists of four parts, two electrodes, a semi-permeable barrier (also known as a separator), and an electrolyte in liquid or solid form (Australian Academy of Science, 2016). The negative electrode is called the anode, and the positive electrode is called the cathode. At the anode, the material that it consists of reacts with the electrolyte and it results in free electrons accumulating at the anode. A chemical reaction also takes place between the cathode and the electrolyte, which enables the cathode to accept electrons. If the two anodes are connected by a wire for example, the electrons will flow from one side to the other, and an electrical current is created. To balance the movements of electrons through the wire, the semi-permeable membrane and the electrolyte allows positive ions to move through it in the opposite direction of where the electrons are going. Bisschop et al (2019) points out that from a safety point of view, the separator's ability to isolate the anodes from each other is very important. If the separator was to break or contract, it could lead to an internal short circuit within the battery cell. This means that the separator must be durable and strong to withstand high temperatures and stresses. If it would be subjected to too high temperatures, the material of the separator could melt and give way to a short circuit and chemical reactions that cannot be controlled, which can lead to an explosion of gases that have been created by the reactions. They also write that the electrolyte is an integral part of both the performance and safety of a battery. One issue regarding the electrolytes commonly chosen for lithium-ion batteries is its flammability, which can vary greatly depending on the chemical compounds used.

Figure 1. *Simplified overview of the battery cell's internal components*



Note: Illustration of the internals of a battery cell. When the battery cell is powering something, the current flows from the anode to the cathode, and when the battery is charging, the electrons flow the opposite way.

Shapes

When thinking about batteries, the common AA or AAA standard cylindrical battery often comes to mind, but they can also come in the shape of a pouch cell or a prismatic cell (Bisschop et al, 2019). The packaging that gives the batteries their shapes are mainly done in three different ways, and all have different pros and cons when it comes to heat regulation, energy density, and ability to withstand stresses. The most common type of battery shape found in vehicles is the prismatic cell, as their rectangular design allows them to be tightly packed and thereby have a high packing efficiency and high energy density, and they also have a rigid outer shell. Pouch cells can also be tightly packed, and their lack of a rigid outer shell allows for the highest energy density out of the three types, but on the other hand it also means that they have an increased vulnerability to external damage. Cylindrical cells can distribute forces evenly over their circumference, which gives them high mechanical stability. However, their shape makes them more difficult to pack tightly together, but this also means that there is more space for air to move around them, which is good for thermal management. Battery packs consist of several battery modules that are connected and arranged together, and the battery modules in turn consist of several connected battery cells.

2.1.2 Battery Safety

Bisschop et al (2019) indicates that the safety concerns regarding batteries are one of the largest obstacles that needs to be overcome to make people comfortable with their presence in the transportation sector. They describe that there are various things that can cause a battery to fail and become unstable and unsafe, for example overcharging the battery, over-discharging, being exposed to too high or too low temperatures, mechanical deformation, manufacturing flaws, and poor electronic control of the battery. Any of these potential faults can lead to a so-called thermal runaway, which can cause gas emissions that can be toxic and/or flammable, and a pressure build-up can lead to the battery exploding.

Mylenbusch et al (2023) describes a thermal runaway as uncontrollable exothermal chemical reactions that develops within a battery cell, which causes the battery temperature to surpass the intended threshold temperature, which further increases the ongoing process, and can result in fire, explosion, and emission of toxic and/or flammable gases. The process of the battery generating more heat than can be dissipated results in a so called "runaway" state which cannot be stopped until all the thermal energy and chemical components have been consumed. This excessive heat can cause fires and build up pressurised gases inside the battery cell as the chemical compounds within begins to degrade, which in turn can cause an explosion.

Bisschop et al (2019) further explain that failures within a single battery cell can spread to other cells, a phenomenon known as thermal propagation. This occurs when the failed battery generates heat that is transferred to the intact cells around it, potentially causing them to have uncontrolled chemical reactions as well. The likeliness of this occurrence, and the speed at which it develops, largely depend on how the battery cells and modules are packed together, with cylindrical cells performing the best because of the airgaps left between the cells and the small contact area they share with each other, and the pouch cells perform the worst as they tend to be very tightly packed. The limiting factors for thermal propagation are the size of the battery pack with bigger battery packs having a higher energy potential and more cells for heat and fire to spread to, and the charge of the battery pack where a higher charge leads to more violent thermal propagation. There is also a correlation between the amount of oxygen in a cell and the propagation speed, as more oxygen makes the heating process faster, and when gas pressure builds up inside the battery, the venting of those gases enables more oxygen to reach the battery and speeds up the process even more.

Moreover, Bisschop et al (2019) state that there is a correlation between the battery's charge level, also known as the state of charge, and the rate at which the energy in the battery is released, as a higher state of charge makes the energy release faster.

Bisschop et al (2019) state that most cases of thermal runaway are caused by abuse or deformation of the battery cell, which can be done in different ways, for example by mechanical, thermal, or electrical abuse. Thermal abuse is when the temperature of battery is not kept within the intended range, electrical abuse can be caused by overcharging for example, and mechanical abuse is when the battery becomes deformed because of various types of impact, for example in a car crash involving an electric vehicle. The impact and consequent deformation of the vehicle's battery pack can cause internal short circuits by rupturing the separator, for instance, leading to a quick energy discharge and rising temperatures, which can trigger a thermal runaway. They also found that a crash may not immediately lead to a fire however, and that the effects of the crash could have a delayed reaction. The probability of a crash resulting in a fire increase with the collision energy of the accident, and the delay of ignition can vary greatly, from igniting instantly, to igniting hours, days, or even weeks after a collision event, sometimes reigniting several times after the fire has been put out. Fires have also been reported to have started without the vehicle being involved in a crash, such scenarios include the car charging for an extended amount of time, being immersed in saltwater, or while being driven.

Mylenbusch et al (2023) write that using water is the most effective way of stopping a thermal runaway, as a large amount of water can act as a heat sink, taking up all the excess heat that is being generated by the battery. Cooling the battery cells will slow down the chemical reactions within it, and perhaps even stop them. There is a risk of the water creating a short circuit of the battery however, and the method of dousing a battery fire should be carefully considered for every individual event.

Bisschop et al (2020) disclose that a battery with a lower state of charge burns in a more “friendly” way, and that when all the flammable materials of a battery have been consumed, there is no longer any risk of fire. Installing a water mist system inside the battery pack that can cool it in the case of increased heat can help prevent a thermal runaway and gas generation in the battery, which int turn can prevent explosion. This can be difficult however, as there can be limited space between the battery cells depending on how they are packed together. The gases generated by an overheated battery can be vented from the battery, but those gases are often toxic and flammable, making the surrounding area unfit for humans.

Willstrand et al (2020) found that the main gases that can be vented from a battery that can be harmful to humans is carbon monoxide (CO) and hydrogen cyanide (HCN) as they inhibit bodily functions, and gases such as carbon dioxide (CO_2), hydrogen gas (H_2), and nitrogen gas (N_2), as they can displace the oxygen within a space, which can lead to asphyxiation. Irritant gases can also be generated, and they can be toxic even at low concentrations. They include sulphur dioxide (SO_2), hydrogen fluoride (HF), hydrogen chloride (HCl), and nitrogen dioxide (NO_2), among others. These gases can be corrosive to the respiratory tract when inhaled, and they can form acids in contact with water. They also found that the concentration of the gases vented from the battery varies with the state of charge of the battery when the reactions occur, with a higher charge leading to a greater generation of carbon monoxide and hydrogen gas.

As a way of mitigating the risks of batteries onboard ships, the European Maritime Safety Agency (2023, November 14) has published a non-mandatory guide on how to integrate lithium-ion batteries on board ships. When it comes to the battery space, they recommend the location of the battery system to be predetermined to enable suitable design and testing of the space, and that the location of the battery space should be in areas of the ship that have a low probability of collision damage, as far as it is practicable.

Furthermore, the European Maritime Safety Agency (2020) also commissioned the classification society Det Norske Veritas to conduct a study on battery systems for the maritime industry. They found that the solid-state electrolyte is a technology that could be well suited for ships, but further development was still needed at the time of investigation. Their suitability stems from the fact that they are expected to pose a lesser fire hazard, as the liquid electrolyte used in most current batteries is flammable, and the solid electrolyte also has the potential of enabling tighter packing of the battery cells.

2.2 Development of Battery Vehicles

Electric vehicles can often be believed to be a recent invention, but they have existed in one form or another since the nineteenth century (Enge et al., 2020). The important inventions and discoveries that laid the foundation for fully electric vehicles were made in the early eighteen hundreds, such as the first battery that could provide a continuous current, the direct current motor, and the relationship between electricity and magnetism. The first electric motor that was able to transport people was installed on a paddle boat and used to carry a dozen people over a river, and four years later the first battery powered locomotive was built. In 1859, the French physicist Gaston Planté presented the first rechargeable battery, and in 1881 Gustave Trouvé, a French electrical engineer, invented the first electric vehicle able to drive on roads.

Burton (2013) explains that in the first year of the twentieth century, almost 40 per cent of all cars sold had electric propulsion. Their popularity stemmed from their ease of use and lack of dirty emissions compared to other types of cars, and the limited range did not become a problem until better roads were built between cities, which made longer trips more common, as car transportation were mostly done within city limits before.

Enge et al (2020) writes that the internal combustion engine and the steam engine were developed around the same time as the electrical motor, and they proved to be a much more economical mode of transportation. As time went on, battery powered vehicles became less popular, especially in north America, since the abundance of oil made it cheaper and more comfortable to own a car with an internal combustion engine.

Burton (2013) informs that the opinion of electric cars turned when the batteries started being too heavy for the vehicles, the electric starter motor made it easier to start internal combustion engines, and the petroleum industry spreading across America made petroleum more easily accessible and cheaper. Petrol stations could be found throughout the country, and refilling the fuel tank was a fast and simple affair, while there were very few battery charging stations outside of large cities. When Henry Ford’s Model T car became widely available and affordable, it took over the American market and the electric car started fading into obscurity.

Enge et al (2020) explains that the rising oil prices in the latter half of the twentieth century led to an increase in interest of electric vehicles again, and Matulka (2014) discloses that NASA also played a part in increasing the interest in electric vehicles, as electric lunar rovers were used in the Apollo space program.

In more recent years, the goal of decreasing global greenhouse gas emissions has made electric vehicles more popular than ever, and the European Environment Agency (2024) has noted that the percentage of newly registered vehicles with electric drive has gone up in the last few years.

Modern electric vehicles rely on large lithium-ion batteries to store the energy needed to drive them. Moseman & Paltsev (2022) disclose that the production of those batteries consumes a lot of energy and resources, but over their life cycle they produce less emissions than a vehicle with an internal combustion engine, which makes them attractive in a world where greenhouse gas emissions need to be reduced.

2.3 Development of Battery Ships

One of the first ships with electric propulsion was the USS Jupiter, which was a naval ship from the United States of America (Babb, 2015). She entered service in 1912 and was the first ship with turboelectric drive and exceeded the economical expectations. More navy vessels were to be built some years later, but the new propulsion system started a controversy between the Bureau of Steam Engineering and several national shipbuilders, as they saw the turboelectric propulsion as a threat to traditional propulsion. The shipbuilders would also be making bigger profits when installing traditional propulsion, as those systems were much cheaper and easier to make than turboelectric drives.

Engineering and Technology History Wiki (2014) states that turboelectric drives were also powered by steam, but instead of mounting the steam turbines directly onto the propeller shaft to rotate the propeller when the steam was let into the turbine, the turbine was mounted separately and drove an electric generator which provided electric motors on the propeller shaft with power. This made the system more efficient and less prone to damage, as the turbines could keep running at a constant speed independent of the rotational speed of the propeller, which can vary a lot when navigating in or out of ports for example.

Babb (2015) reports that several more navy ships with turboelectric drive were built in the following years, but they never proved to be so much more efficient than their mechanically driven counterparts as they were expected to be, so the use of turboelectric drive was eventually phased out from the navy.

Paul (2020) explains that electric propulsion of ships became more relevant when the fuel prices rose, and exhaust emissions faced stricter regulations. The use of electric propulsion proved to increase the efficiency of the system, which reduced the exhaust emissions. As larger batteries developed, they became more prevalent to use onboard ships for various purposes, such as to reduce emissions, or as an uninterruptable power supply.

Wärtsilä (n.d) defines a fully electric ship as a ship that relies on batteries to power every system that is onboard, including the propulsion system, heating, ventilation, etc. If the electricity comes from fully renewable sources, it enables the ship to operate with zero emissions of carbon dioxide during its operational lifetime.

The World’s first fully electric ferry entered service in May 2015 between the Norwegian towns of Lavik and Oppedal. Mikkola et al (2016) explains that the ferry, named Ampere, is powered by lithium-ion batteries and transports passengers and vehicles across the Sognefjord as part of the E39 road route, and one crossing is completed in roughly twenty minutes.

Anwar et al (2020) state that the battery propulsion does come with its limitations however, most notably the range of operation of the ship. This comes as a natural consequence to electric propulsion, since the batteries need to be recharged in a port that has the necessary infrastructure to supply the huge amount of power that the ship batteries demand. The quantity and type of batteries that the ship carries will also have a maximum amount of power that can be supplied to necessary systems, and when that power runs out, the only way to be operational again is to recharge the batteries. This makes battery propulsion more suitable for ships that travel only over short distances and between predetermined ports, and ferries are a good example of a ship that does just that. Ferries mostly carry passengers and Ro-Ro cargo between ports that are geographically close to each other, and they have a regular schedule of when they are to be on what location. The battery type chosen for maritime propulsion is often lithium-ion batteries, as they can be charged quickly, they are cost-effective, they have good safety specifications, they are lighter and more energy dense than some other battery types on the market, which will help improve the efficiency of the ship.

The development of fully electric ships is ongoing in several parts of the World, for example, Stena Line (n.d.) has a vessel in development that will be entirely free from emissions and fossil fuel. ‘Stena Elektra’ is planned to travel between the port of Gothenburg and Frederikshavn before the year 2030 and will be able to carry up to 1500 passengers as well as RoRo-cargo.

To operate such a large vessel solely on battery electric propulsion is no small feat, which is made obvious when comparing the batteries of road vehicles and those used on ships. Trombetta et al (2024) explained that the capacity of a car battery generally is around 60 kWh, and a truck has a capacity of 1000 kWh, while a small commuter ferry requires a battery capacity of 4,3 MWh and a RoRo ferry can require up to 70 MWh worth of battery power.

According to the European Alternative Fuels Observatory (n.d.) there were 125 vessels worldwide that were fully electric in the year 2022, and the most common ship type with fully electric operation is the car/passenger ferry.

2.4 Maritime Regulations

The maritime sector is subject to several different conventions and codes which have requirements and demands regarding, among others, safety, security, and pollution prevention. The requirements differ somewhat depending on the type of ship, the intended operational location, and the size of the ship.

Ships are of course subject to those regulations, codes, conventions, and standards, but the demands can differ somewhat depending on the trade route, weight, and the type of cargo the ship will carry. The requirements that ship face have developed and increased over the years, which most commonly happens after the occurrence of incidents or accidents that have shown weaknesses in the current system. Two of the most important conventions are the International Convention for the Prevention of Pollution from Ships (MARPOL) and the International Convention for the Safety of Life at Sea (SOLAS), which covers pollution prevention and safety of life respectively.

The SOLAS convention is one of the most prevalent and important conventions in the maritime industry and handles every subject that affects the safety and stability of ships (International Maritime Organisation, n.d.C). The convention has created and specified standards that are the minimum requirements for ships to have regarding their operation, construction, equipment, and safety.

The MARPOL convention came about in 1973 and was further improved upon after an increase of accidents involving tank ships in around 1977, and it has been further improved upon over the years (International Maritime Organisation, n.d.D). The convention covers several different types of pollution, but the emission of harmful substances into the sea is the most prevalent type of pollution that is to be prevented. Two of the earliest MARPOL annexes covers the prevention of oil pollution and the prevention of noxious liquid pollution, which were added in 1983.

MARPOL covers measures to ensure the safe operation of ships when it comes to all substances that can potentially be emitted into the sea, including both substances that are allowed to be emitted and those which are not. Substances that are allowed to be emitted into the ocean shall be done so under controlled circumstances and need to be documented properly, and emissions that are not allowed, for example oily substances and dangerous chemicals, need to be documented meticulously too. The convention also states some demands that need to be followed when a ship is constructed, which are meant to prevent harmful substances from entering the ocean if an accident would occur. Those construction demands will be used as guidelines when it comes to evaluating what areas on a ship are deemed less safe for placement of certain things or substances.

The International Maritime Organisation (n.d.A) uses Formal Safety Assessments (FSA) as a tool to create new regulations and to develop existing ones, with the goal to further enhance the safety, security, and pollution prevention of the maritime industry. This is done by identifying potential risks and evaluating them, and to compare the likelihood of an accident and how much effort and money would need to be spent to reduce that accident from happening.

A Formal Safety Assessment usually consists of five steps:

1. Identification of hazards
   What could go wrong? Identify all scenarios and activities which could pose a risk to those involved, and then identify what could cause an accident and what could be the result.
2. Assessment of risks
   How bad could something go wrong and how likely is it to happen? Identify what type of injury or damage the specific scenario could cause, how dangerous that would be, and estimate how frequently such an incident is likely to occur.
3. Risk control options.
   Can something be done to reduce the risk? Analyse potential factors that could help reduce either the severeness of the injury or damage, the frequency of the incident occurring, or both.
4. Cost benefit assessment
   What would a control option cost and how effective would it be? Investigate if the cost of implementing the risk reduction measure would be justified by how much it would decrease the risk.
5. Recommendations for decision-making
   What should be done about the hazard? Compile all the previous information in a presentable way, this will be the basis for the recommendations in the decision-making process.

If the risks assessed in step two are deemed to be too great, the next step investigates if the risk can be reduced either by making the accident less frequent or by mitigating the severity of the consequences. Those risk control options are then compared to the cost of implementing them in step four, and the last step is to come to a conclusion on what should be done about the risk.

2.5 Ship Design Requirements

In the case of ships that carry oil as cargo, MARPOL requires them to have a double bottom and double side hull constructed to protect the cargo oil tanks. The International Maritime Organisation (n.d.E) regulation 19 states that the distance between those hulls is to be measured at right angles from the inside surface of the outer hull. They also state in regulation 16 that no oil shall be carried forward of the collision bulkhead.

The International Association of Classification Societies (2024) writes that the extent of the double bottom hull on oil tankers is to be fitted in such a way that it protects the cargo spaces, and thereby gives no specific demands on how far the double hull spaces need to extend along the length of the ship, provided that the cargo tanks are protected.

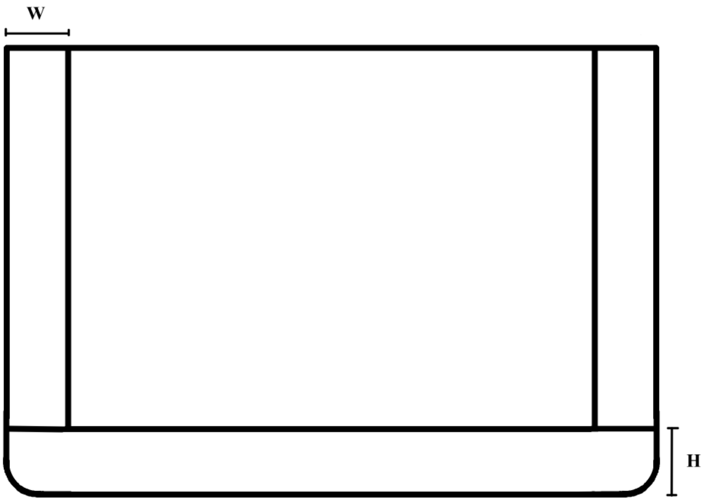
Oil is not only carried as cargo however, as it is also used as fuel for the ship, and it is then carried in bunker tanks. Construction of bunker tanks and cargo tanks does not follow the same requirements. The International Maritime Organisation (n.d.E) regulation 12A states that individual fuel oil tanks cannot carry more than 2500 m^3 of fuel, while regulation 26 states that cargo oil tanks can carry up to 50.000 m^3 of oil, with the actual applicable volume depending on the placement of the tank. The smaller tank volume of bunker tanks means that the construction distance safety margin is slightly lower than for cargo tanks. The side measurements between the hulls are the same for both tank types, namely at least one meter and at most two meters, but the distance between bottom of the hulls is different for cargo tanks and bunker tanks. The distance must be at least 0.76 meters and at most two meters for bunker tanks, and at least one meter and at most two meters for cargo tanks. The hull transitions from bottom to side at 1,5 times the distance between the hulls at the bottom. Figure 1 and Table 1 can be used to get an overview of the distances required and how the affected compartments are situated.

Table 1. *Double hull distance measurements.*

Tank type	H_{min} (m)	H_{max} (m)	W_{min} (m)	W_{max} (m)
Oil cargo tanks	1	2	1	2
Oil bunker tanks	0,76	2	1	2

Note: The information in this table is gathered from the ‘MARPOL convention annex I’ by the International Maritime Organisation (n.d.E). http://dmr.regs4ships.com/ . This is a compiled list of distance measurements that are demanded by MARPOL when constructing a double hull.

Figure 2. *Simplified cross section of a double hulled ship.*



Note: Simplified cross section of the cargo hold on a double hulled ship, such as an oil tanker. H signifies the distance between the double bottom hulls, and W signifies the distance between the sides of the double hull.

The International Maritime Organisation (n.d.F) regulation 12 states that a collision bulkhead shall be constructed and extend up to the freeboard deck or the bulkhead deck on cargo ships and passenger ships respectively. The collision bulkhead shall not be closer to the forward perpendicular than 5% of the ship's length or 10 meters, whichever distance is smaller. The collision bulkhead shall also not be constructed farther from the forward perpendicular than 8% of the ship's length or 5% of the ship's length plus 3 meters, whichever distance is greater. The area that remains between the two distances is the location where it is acceptable to construct the collision bulkhead.

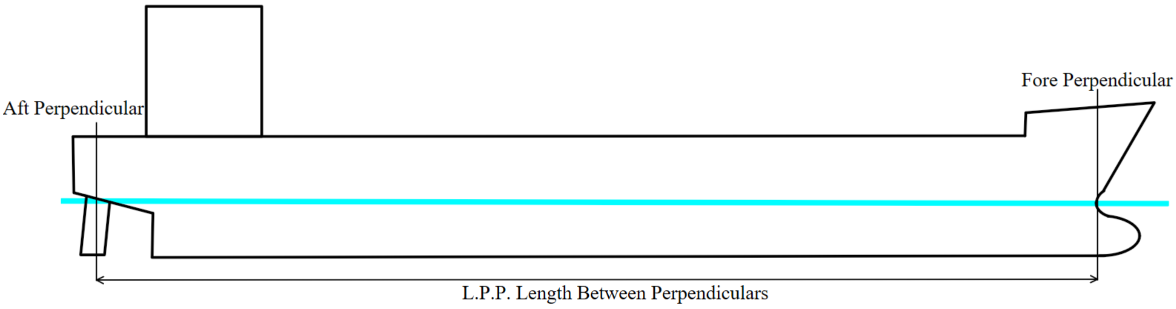
The length of the ship used when calculating the distance of the collision bulkhead is the distance between the perpendiculars, as defined by the International Maritime Organisation (n.d.D) in chapter I regulation 3. The forward and aft perpendiculars are found at each end of the ship's length, which can be defined as the distance along the waterline between the front of the stem to the axis of the rudder. This means that the forward perpendicular is at the front of the stem where it meets the waterline, and the aft perpendicular is placed along the axis of the rudder stock. Figure 3 shows a visualisation of the location of the perpendiculars and the ship's length.

Table 2. *Requirements on the construction location of the collision bulkhead.*

	Min	Max	
Closest distance to forward perpendicular	5% of L	10 meters	Choose the smaller value
Furthest distance to forward perpendicular	8% of L	0.05% of L + 3 meters	Choose the greater value

Note: The information in this table is gathered from the SOLAS convention chapter II-I by the International Maritime Organisation. (n.d.F). http://dmr.regs4ships.com/

Figure 3. *A visualisation of a ship's perpendiculars and length*

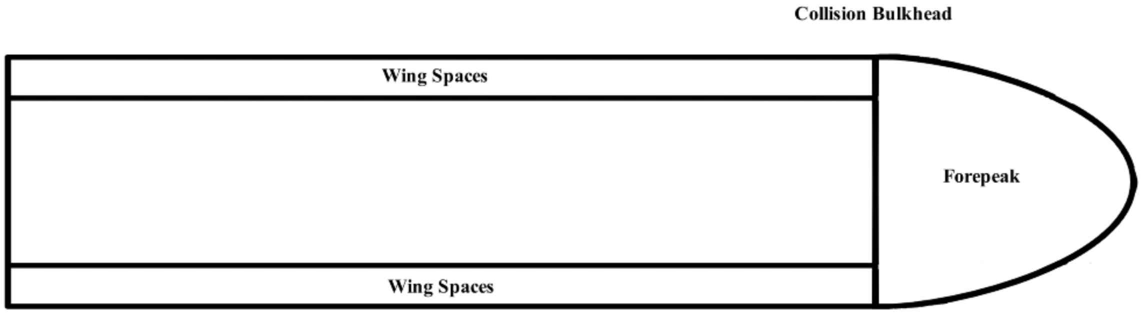


Note: The distance named L.P.P, or Length Between Perpendiculars is another name for the length of the ship.

The International Association of Classification Societies (2024) state that all ships must have a collision bulkhead and an aft peak bulkhead. The aft peak bulkhead should enclose the rudder trunk and the stern tube in a watertight compartment, alternative arrangements can however be made if the previously stated requirement is too impractical. The previous requirements are also expressed by the International Maritime Organisation (n.d.F) in regulation 12.

The International Association of Classification societies (2024) describes the area forward of the collision bulkhead as the fore peak. This area often contains a ballast tank which can be filled or emptied depending on the cargo load conditions. There shall also be an afterpeak bulkhead fitted, and it is to be located at the aft end of the machinery space, and the aft peak is located aft of the aft peak bulkhead. The aft peak often contains a ballast water tank, just as the forepeak does.

Figure 4. *Ship overview with collision bulkhead.*



Note: A simplified illustration of the collision bulkhead and forepeak area seen from above. The wing spaces usually contain ballast tanks.

2.6 Maritime Accidents

Several different organisations and agencies worldwide record the number of accidents and incidents occurring every year, for example the Swedish Transport Agency and the European Maritime Safety Agency (EMSA). They present annual overviews of accidents and incidents that have occurred in the maritime industry in Sweden and Europe respectively and organise the data into statistics. The likelihood of maritime accidents increased with a growing trade, and Zhang et al (2019) explain that such events can lead to substantial damage of the environment, cargo, and human life as well. The European Maritime Safety Agency (2017) states that more than 3000 accidents and incidents are reported to them every year, and that some of the most common accident causes are collision, contact, and grounding.

3. METHODS

The methods used are presented in this chapter. The websites used to gather information, the keywords used in the search for sources, and the choice of sources and their reliability will be disclosed. The method used for the risk assessment is also presented.

3.1 Overview

In the search for sources to be used in this report, the databases of Chalmers University library and Web of Science were used to find informative and relevant academic articles, and Google was used to find publications on statistics, guidelines, and safety matters related to the topics of this report. Keywords applicable to the subjects were used in the information search, and they evolved as the search process went on, and new words were also added to make the searches more specific. Filters were added during the searches to narrow down the results, the sources found were checked for relevancy, and those applicable to the topics at hand were examined. This procedure was used to find information for both the Theory chapter and the Results chapter, however the sources used in the Results chapter faced stricter criteria when evaluated, which are explained in chapter 3 section 2.2 and section 3.

3.2 Literary study

This report was conducted as a systematic literary study. The eBooks *The Good Research Guide* by Martyn Denscombe and *Doing Your Literature Review* by Jill K. Jesson, Lydia Matheson, and Fiona M. Lacey were used as guidelines when writing this report.

Denscombe (2014) explains that a literary study demands a more meticulous investigation into sources, and the method used when finding, evaluating, and choosing sources shall be transparent and clear. The purpose of a literary review is to examine what previous work has been done within a field of research or subject of study, and to come to conclusions based on the evidence and research found. A systematic literature review aims at lessening the potential bias by informing the readers about how the study and source finding was conducted, and how the decision to include or exclude sources was made.

3.2 Method of Searching

Various sources in the form of academic articles, eBooks, websites, and publications were found through several different search engines, websites, and databases. The information found was evaluated, compiled, and presented in the Results chapter. All information searches were done between the 5th of February and the 5th of May 2024, during the period when this report was scheduled.

3.2.1. Search Engines and Databases

When searching for academic sources relating to the relevant subjects, the databases of Chalmers University Library and Web of Science were used. Both databases and their search engines, as well as the Regs4Ships website, which is a maritime regulation database, were accessed through the Chalmers University Library website. These databases and search engines were determined to be enough, as using more search engines would have made the information search too extensive and take too much time for the purpose of this report.

The information search began at the Chalmers University Library as it was familiar to work with. In addition to Boolean search operators, the website features six different types of filters that can be applied to the search results to find sources with the right subject focus.

Web of Science was used after a recommendation from a librarian at Chalmers University. The Web of Science database features sources in the form of academic articles, conference proceedings, and book chapters to name a few. In addition to Boolean search operators, this search engine and database offers several additional appliable filters that can be used to find relevant sources, compared to the Chalmers University Library website.

No search words or phrases were needed when finding SOLAS and MARPOL through the Regs4Ships database, as they were easily found at the home page of the website when logged in. SOLAS and MARPOL were examined for information on ship design and construction requirements. ILLC was found by searching for ‘load lines’ on the website.

Google was also used as a search engine to find sources. The sources found were the websites of various agencies, organisations, companies, and institutes, which had relevant information on battery vehicles, battery ships, statistics, guidelines and conventions for the maritime industry, and similar topics. Jesson et al (2011) explain that these types of sources are known as ‘grey literature’, which is any source that is not an academic journal article, such as technical reports, reports commissioned by an organisation, policy reports, and these types of sources require special care when assessed. These sources will be presented here.

Det Norske Veritas: A maritime classification society and a member of the International Association of Classification Societies.

European Environment Agency: An agency of the European Union with the purpose of collecting, validating, and delivering data and knowledge that is used to support climate and environmental goals in Europe. The European Union uses this data to create new policies or develop existing ones.

European Maritime Safety Agency: A decentralised agency of the European Union located in Portugal. Their purpose is to provide information and guidance to governments and authorities with the goal of improving maritime safety and security, and to prevent various forms of pollution from the maritime industry.

Eurostat: The statistical office of the European Union with the purpose of providing the union with high quality data and statistics on Europe.

International Association of Classification Societies: An organisation consisting of recognised classification societies with the goal of regulating and improving ship construction, safety, pollution prevention, and maintenance. They provide technical and operational expertise to regulatory bodies and the maritime industry, with standards that are globally uniform. The organisation is a technical advisor to the IMO.

International Maritime Organisation: A specialised agency within the European Union which regulates safety, security, and pollution prevention of the maritime industry in several different ways, such as ship construction, equipment, operation, and disposal. The rules they create are universal for all member nations, and make sure that ship owners and others cannot compromise on safety, security, or pollution prevention to save on costs.

Massachusetts Institute of Technology Climate Portal: A website founded by Massachusetts Institute of Technology with the goal of providing people with science-based information about climate change, its causes, consequences, and what can be done and is being done about it.

Nordregio: A Nordic research institute founded by the Nordic Council of Ministers. It is included among the research entities of the Statistical Office of the European Union and conducts research on, for example, regional development, urban planning, and other projects that can face environmental, economic, and social challenges.

RISE Research Institute of Sweden: A research institute founded and owned by the Swedish government. Their goal is to contribute to the innovative development of society, and that they are to do so by conducting high-quality research, encourage cooperation between the academic sector and the trade and business industry. The organisation consists of researchers, scientists, and experts in various fields of innovation.

Swedish Transport Agency: An agency of the Swedish government that handles for example regulations, permits, and supervision of all things concerning the transport sector. Their work covers all types of transportation, including railroads, air travel, and shipping.

U.S. Department of Energy: A department within the federal government with the mission to address energy, environmental, and nuclear challenges in America through transformative solutions of science and technology.

3.2.2 Search Process

Broad keywords and search phrases were used in the beginning of the information search process to get an overview of the topics, and the process of finding interesting sources made the search terms and words evolve and become more specific. The new keywords were added to the existing ones to narrow down the search results. When conducting the information search, the subject of the report was divided into two main branches to streamline the process, the branches were *Ship design and accidents statistics* and *Battery design and damage statistics*. The keywords and phrases used were:

General keywords: *Ship, Battery, Safety, Propulsion, Electric, Collision, Vehicle, Accident*

Specific keywords: *Mechanical abuse, Double hull, Maritime industry, Statistics, Lithium-ion, Deformation, Thermal runaway,*

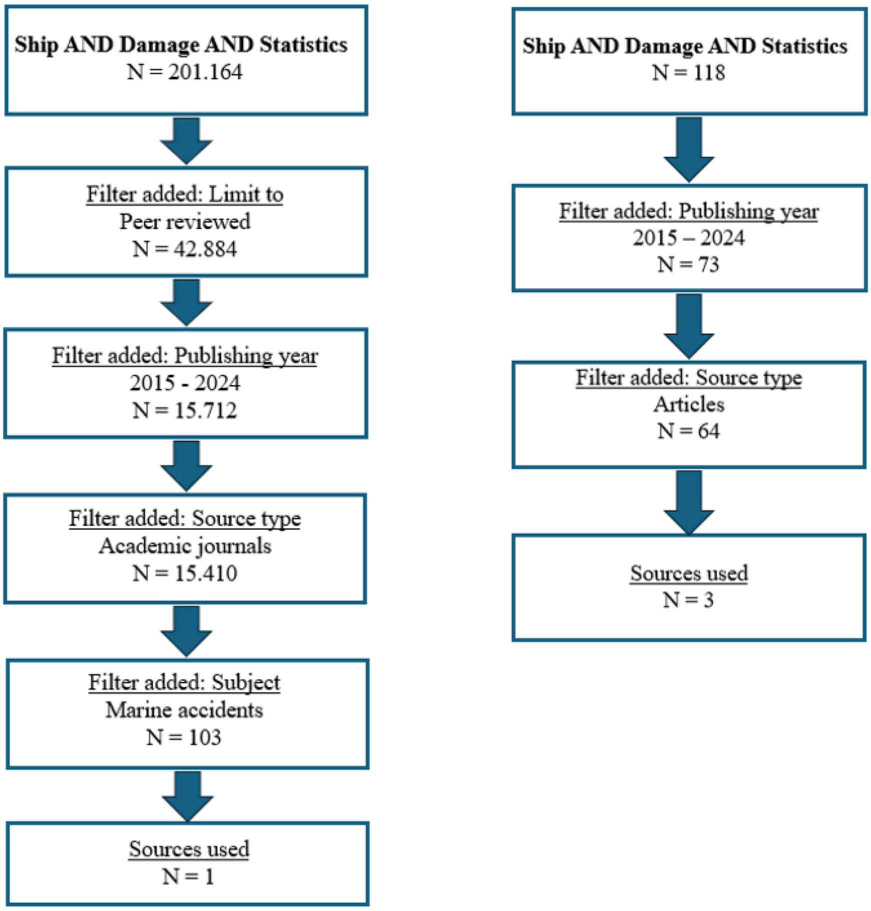
Additional keywords (used as filters): *Marine accidents, Double hull, Lithium-ion battery, Mechanical abuse, Battery protection,*

Multiple keywords were used at the same time in various combinations, along with Boolean search operators. Filters in different forms were then added to the search terms to further narrow down the search results, the filters used were as follows:

- Year of publication. The publication time span was limited to the years 2015-2024. This was because the development of electric vehicles and ships has progressed quickly within the last decade, and older results were estimated to be less relevant than more contemporary publications. The timespan of the sources was therefore limited to within ten years from this report being written.

- Type of source. The source types were limited to academic articles or journals.
- Peer review. When looking specifically for academic articles, the Peer Review filter was added to find more credible sources.
- Additional keywords. This applies both to the Chalmers University Library search engine and to the Web of Science search engine, but they differ somewhat in their design. In Web of Science, additional keywords appeared after conducting a search. The search operator of those added keywords could be changed to 'should include' and 'must include', or 'do not include' to further narrow down the results. The Chalmers University Library has a drop-down menu where additional subjects can be added as a filter to the original search words or phrase.

Table 3. *The search process of the information search when using the keywords "Ship AND Damage AND Statistics", and how they were narrowed down using search filters. The result from Chalmers University Library is presented on the left, and Web of Science on the right.*



Note: When the sources had been narrowed down to the second to last step of the ones shown above (N = 103 and N = 64), the titles of all the results were read, and if the article appeared to be relevant, the abstract was also read. The last step shows how many of the articles were included as sources in the final report.

The title and the abstract of the articles were read first to discern the relevancy of the source. Those articles regarded as having high relevancy were further investigated by reading the introduction and conclusion, to determine if the source was applicable to this report (Jesson et al, 2011, p 115). The articles found to be relevant were scanned in their entirety and browsed for important data to include in the report, and the source was added to the bibliography. This process was repeated for both Chalmers library and Web of Science for each combination of search words used.

When using Google to find sources, the process was different. Search phrases were constructed using the some of the keywords as stated above in section 3.2.2, but without using Boolean search operators and instead using prepositions to formulate a coherent search phrase. The inclusion criteria the sources faced were a publication year between 2015-2024, they had to be written in Swedish or English, and they had to be published by reputable agencies, organisations, or institutes.

3.3 Evaluation of Sources

The sources used in this report were evaluated according to the CRAAP test (Library Guide at the University of Chicago) to investigate the relevance, currentness, accuracy, and potential bias of the information found. Some of the search filters described in section 3.2.2 were used to find sources with high relevancy and accuracy, for example by finding recent articles that have been peer reviewed. The publishing date of the sources was deemed to be an important criterion to meet to ensure that the results found were contemporary, as older articles and publications may contain information that is no longer relevant or accurate. Furthermore, the articles being peer reviewed was an important criterion as well, since their quality is investigated more meticulously by other experts within the field before being published. The academic articles that were found and had been published in magazines were checked for quality by using UlrichsWeb to determine whether that magazine practices peer review of the articles they publish. Sources that were deemed too advanced for the purpose of this report were scanned but not included, and the sources of the articles could be investigated further if it appeared that they could be relevant.

Sources that were not academic articles were evaluated using the CRAAP test as well, and special care was taken to investigate the organisation, institute, or agency that had published the source. Their connection to other reputable and official bodies was examined to ensure the credibility and relevance of their publication. The authors of these types of sources are presented in chapter 3 section 2.1 – Search Engines and Databases of this report.

3.4 Results of the Information Search

As the information search went along, some issues arose along the way. Many of the potential sources found were too advanced for the purpose of this report, as they utilized advanced mathematical models, and many of them were not applicable to this report, as they did not utilize simulations or statistics. Finding sources about distribution of different accident types within a certain number of reported maritime accidents was straightforward, while finding reliable statistics on the number of accidents occurring in relation to the total amount of ship movements within an area proved to be more difficult. It was also difficult to find exact and definitive answers regarding the deformation limits of batteries, as there are many factors that play a part in how a battery deforms.

It was also challenging to find information on collision safety of the fully electric ships that already exist, as they are quite few, have not been operating for very long, and they seem to not have been involved in any accidents.

Some of the sources used could be found through both the Chalmers University Library database and Web of Science, and if those sources had either been included or already been investigated and deemed to be irrelevant or unsuitable, they were swiftly disregarded during the other searches when they appeared. Some sources were found by examining the sources of the articles and publications found through the search engines and databases.

3.5 Risk Assessment

The risk assessment in this report is based on the steps of IMO’s Formal Safety Assessment mentioned in chapter 2.4 Maritime Regulations. However, there is two major and three minor changes to the approach of the risk assessment in this work, compared to the original procedure presented by the International Maritime Organisation (n.d.A). The changes are as follows:

Major changes

1. Step number four, which covers the cost benefit assessment, is excluded from this report. This is due to one of the delimitations stated in chapter one, namely that economical standpoints are not to be considered in any way in this report.
2. The table used to determine the frequency of a scenario occurring is altered to be applicable to only one ship, instead of the fleet of ships that is normally used. The frequency is calculated in “per port call” instead of “per ship year”.

Minor changes

1. Step number one is shortened, as there is a finite number of scenarios that are identified and considered in this report, meaning that not all scenarios and activities that could pose a risk are identified.
2. The effect on human safety is not considered and evaluated for a severity index, only the effects on the ship.
3. The table used to determine the severity of an accident will have additional descriptions of ship damage added to the existing ones, to better present the damages expected on the different levels.

Methods that can be used while performing a risk analysis include using accident and failure data (International Maritime Organisation, 2018), which is the basis for the analysis and assessment in this report. Statistical data and simulation data on maritime accidents is presented in the Results chapter, and the findings are synthesized into numbers that are used when performing the risk analysis. The outcome of the results is discussed in the Discussion chapter, where Appendix number 4 in the document created by the International Maritime Organisation (2018) is used in combination with the results to evaluate the risks by determining the frequency and severity of an accident. Statistics on the number, nature, and distribution of accident types is used to evaluate the likelihood of a ship being damaged, and the statistics and simulation data on the extent of hull damage is used to evaluate the severity of the accident. The statistics and simulation data on the location and extent of damage on a ship's hull is used to evaluate where batteries face higher risk of deformation, and what locations would be better suited to contain batteries.

3.6 Ethics of the Information Search

As there is no data collected from individuals during this study, there is no need to gain anyone's consent on data collection or personal information being published. Ethics regarding consent of participants is important, but it is not applicable in this report. In a systematic review it is instead important to ensure that the data collected is truthful and not interpreted in an inaccurate way. The data collected should also be quality checked to ensure that the source or its authors are not biased or skewing the results, which was done by confirming that the articles had been peer reviewed. When it comes to grey literature, that becomes more difficult, as the sources are often written and published by governmental agencies or similar organisations that are not fact checked to the same extent. In such situations the publisher and their purpose were investigated, as well as their relationship to other organisations that are highly esteemed within the industry. The information found was gathered and compiled in a structured way, but no information from the sources were changed to fit into a predetermined narrative, which would rid the report of its credibility.

4. RESULTS

The results found in the information search is presented, and the statistical and simulation numbers are synthesised in preparation for use in the discussion chapter.

4.1 Overview of Results

This section gives and overview of the sources and results found in the information search. The total number of sources used in the results chapter is 20.

Table 4. *Categorisation and numbers of sources found.*

Subject	Number of sources
Deformation of batteries	7
Electric Vehicle safety	2
Maritime accident statistics	6
Hull damage extent	3
Batteries onboard ships	2

Note: This table displays the numbers of sources found within each type of subject. A more detailed table on the sources can be found in appendix 1.

4.2 Number and Nature of Maritime Accidents – Statistics

Many different organisations and agencies keep a record over maritime accidents and incidents, for example the Swedish Transport Agency, EMSA, and IMO. The scope they cover are different and can overlap, for example because EMSA covers accidents in Europe and European ships all over the world, and the numbers recorded by the Swedish Transport Agency is naturally a part of those accidents recorded by EMSA.

4.2.1 Recorded Number of Accidents and Incidents

Eurostat (2023) compiles statistics on the maritime industry for the benefit of the European Union, covering things such as the weight of seaborne freight, what type of cargo that is handled, and the import and export ratio of the freight for each country of the union. One part of their statistics is also the number of port calls that has been made by vessels in main ports in Europe during each year. They found that approximately 2 million port calls are made in main European ports every year. The documented total number of port calls made each for each year between 2018-2022 can be found in table 5. The actual number of port calls in Europe is much higher however, as main ports are defined as ports that handle more than one million tonnes of goods or 200.000 passengers every year.

Table 5. *The number of port calls made in main European ports.*

Year	2018	2019	2020	2021	2022	Average
Port calls	2.189.422	2.278.469	1.944.030	1.993.617	2.232.354	2.127.578,4

Note: The information in this table is gathered from table 2 in the publication "Maritime Freight and Vessel Statistics" by Eurostat (2023, December 13). https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Maritime_ports_freight_and_passenger_statistics&oldid=218671
Main ports are defined as ports that handle more than one million tonnes of goods or 200.00 passengers every year, which means that not all port calls in Europe are recorded here.

During the same period, 2018-2022, the European Maritime Safety Agency (2023, October 27) recorded a combined average of 800 serious and very serious marine casualties. These two types of categorisations cover ships that have sustained damage that results in severe structural damage, like the hull being ruptured under the waterline, or even the loss of the ship, as a consequence of for example collision, grounding, or contact, to name a few.

Table 6. *The number of marine casualties recorded by EMSA in 2018-2022.*

	2018	2019	2020	2021	2022	Average
Serious casualties	824	759	724	747	612	733,2
Very serious casualties	106	75	51	58	44	66,8
Total casualties	2669	2782	2594	2692	2510	2649,4
Combined percentage of casualties	34,8%	29,9%	29,8%	29,9%	26,1%	30,2%

Note: The information in this table is gathered from the publication "Annual Overview of Marine Casualties and Incidents 2023" by the European Maritime Safety Agency (2023, October 27). https://www.emsa.europa.eu/publications/reports/item/5052-annual-overview-of-marine-casualties-and-incidents.html

Only the serious and very serious marine casualties from the publication are featured in this table.

The Swedish Transport Agency (2023) compiles and publishes safety overview reports concerning the maritime industry each year, which features statistics of accidents reported to the agency. They have noticed a recent increase in the number of reported accidents and incidents, but still believe that the number of unreported incidents is high. Between the years 2018-2022 there was on average 9,4 marine accidents per 10.000 port calls in Sweden. The yearly reported accidents and incidents during the period 2018-20222 are shown in table 7.

Table 7. *Accidents and incidents reported per 10.000 port calls in Sweden 2018-2022.*

Type of occurrence	2018	2019	2020	2021	2022	Average
Marine accident	8	7,5	9,1	13,3	9,1	9,4
Marine incident	3	4,5	8,1	7,5	12,9	7,2

Note: The information in this table is gathered from the publication "Säkerhetsöversikt sjöfart 2022" by the Swedish Transport Agency (2023, May 29). https://www.transportstyrelsen.se/sv/publikationer-och-rapporter/rapporter/sjofart/sakerhetsoversikt-sjofart-2022/ .

Marine accident signifies the number of actual accidents that has happened, and marine incident signifies the number of occurrences that could have turned into accidents if they had not been avoided.

Sormunen et al (2016) conducted a study on maritime accidents in the Baltic Sea, examining the most common accident types and their causes, as well as how many port calls were made in Baltic ports. They found that more than 450.000 port calls were made in Baltic ports each year, based on statistics from Eurostat combined with estimations on port visits in Russia. The results are shown in table 8.

Table 8. *The total number of port calls in Baltic ports between 2006-2011.*

	2006	2007	2008	2009	2010	2011	Average
Total number of port calls	475.319	489.767	505.178	470.169	468.234	475.119	480.631

Note: The information in this table is gathered from the article "Marine traffic, accidents, and underreporting in the Baltic Sea" by Sormunen, O.V.E., Hänninen, M., & Kujala, P. (2016). *Scientific Journals of the Maritime University of Szczecin*, 118(46), 163-177. https://repository.am.szczecin.pl/handle/123456789/1224

Sormunen et al (2016) also found that that the most common accidents reported in the Baltic Sea during the period 2006-2011 was grounding, contact, and collision, the numbers are presented in table 9. Nevertheless, they estimate that the actual number of accidents in the area is much higher, and that the real number or accidents are at least double the number of recorded accidents.

Table 9. *Accidents reported in the Baltic Sea during 2006-2011.*

	Collision	Contact	Grounding	Total number of accidents
Number of accidents	92	122	236	653
Percentage	14,1%	18,7%	36,1%	100%

Note: The information in this table is gathered from the article "Marine traffic, accidents, and underreporting in the Baltic Sea" by Sormunen, O.V.E., Hänninen, M., & Kujala, P. (2016). *Scientific Journals of the Maritime University of Szczecin*, 118(46), 163-177. https://repository.am.szczecin.pl/handle/123456789/1224

4.2.2 Accident Location Type

When it comes to the type of waters navigated as the accident took place, the Swedish Transport Agency (2023) found that they most commonly occur close to shore or ports. Accidents in port areas account for one in four occurrence locations and is therefore the most common accident location. Even so, the numbers have gone down compared to the previous year (2021), when the port area accounted for 38% of all accident locations in Swedish waters. The distribution of the accident locations is displayed in table 10.

Table 10. *Distribution of marine accidents based on type of location.*

Type of water navigated	Percentage of marine accidents
Port area	25%
Cramped coastal waters	19%
Coastal waters close to shore	12%
At berth, dock, etc.	11%
Channel, river, shipping lane marked with buoys	7%
Lakes	5%
Open coastal waters	4%
Open ocean	3%
Unknown	14%

Note: The information in this table is gathered from the publication "Säkerhetsöversikt sjöfart 2022" by the Swedish Transport Agency (2023, May 29). https://www.transportstyrelsen.se/sv/publikationer-och-rapporter/rapporter/sjofart/sakerhetsoversikt-sjofart-2022/

The areas close to shore, ports, and shipping lanes represent the majority of the areas where maritime accidents occur.

The statistics from table 10 illustrates the findings of the Swedish Transport Agency (2023), and they further theorise that accidents occurring in regions close to shore are more likely to be reported, as there are more people and ships in the surrounding area that can observe the accident and report it. Regarding accident locations Antão et al (2023) mention that ships that have a higher number of port calls are at a higher risk of collision since doing coastal navigation makes them exposed to high traffic more frequently.

The accident and incident locations that the European Maritime Safety Agency (2023, October 27) recorded during the years 2014-2022 shows that the trend of a higher number of accidents and incidents occurring in port areas compared to other locations is a trend that not only applies to Sweden. They recorded that 51,5% of the casualties reported during that period had occurred in inland waters, out of which 39.6% were in port areas. This is comparable to the 38% of accidents that the Swedish Transport Agency (2023) recorded to have happened in port areas in Sweden during the year 2021.

4.2.3 Distribution of Accident Types

There are many different types of maritime accidents and incidents that can occur, but those that are more likely to result in hull damage are collision, contact and grounding. The European Maritime Safety Agency (2023, October 27) defines a collision as an event where one ship is striking or being struck by another ship, a contact event is when a ship strikes any external object that is not another ship or the ground (for example a berth, floating obstacle, or a man made structure) and grounding is an event where a navigating ship strikes the sea bottom, underwater wrecks, or the shore.

The records kept by the Swedish Transport Agency (2023) on accident events show that those types of occurrences on average account for 42% of the initial events of all accidents reported. This means that collision, contact, and grounding events as a consequence of some other initial occurrences are not recorded in that percentage. The number of accidents for the period 2018-2022 can be seen in table 11 below.

Table 11. *Relevant accidents compared to all the reported accidents each year.*

Type of accident	2018 (%)	2019 (%)	2020 (%)	2021 (%)	2022 (%)	Average
Collision with foreign object	18 (10%)	18 (12%)	24 (13,1%)	32 (14,7%)	41 (20,1%)	26,6 (14,3%)
Collision with other ship	19 (10,5%)	16 (10,9%)	25 (13,6%)	26 (12%)	20 (9,8%)	21,2 (11,4%)
Grounding impact	33 (18%)	31 (21%)	32 (17,5%)	31 (14,3%)	25 (12,3%)	30,4 (16,3%)
Total number of accidents each year	180	147	183	217	204	186,2

Note: The information in this table is gathered from the publication "Säkerhetsöversikt sjöfart 2022" by the Swedish Transport Agency (2023, May 29). https://www.transportstyrelsen.se/sv/publikationer-och-rapporter/rapporter/sjofart/sakerhetsoversikt-sjofart-2022/.

These numbers only represent the initial accident occurrence, meaning that collisions due to other causing factors, for example loss of steering, are not included. It is important to note that the collisions registered between ships is registered once per ship, not once per occurrence. The results from the publication by the Swedish Transport Agency (2023) that were not relevant to this report have been excluded from the table.

The Swedish Transport Agency (2023) points out that the collisions recorded by them is registered once per ship involved in the collision, not per instance of a collision occurring.

EMSA also keep records of reported accidents and incidents, and their statistics for the same period can be seen in table 12 (European Maritime Safety Agency, 2023, October 27). They found that the casualty event 'Collision' has been surpassed by 'Loss of propulsion power' in recent years, breaking the trend of the previous years. The number of 'Contact' occurrences has remained stable, and the number of 'Grounding' occurrences has been decreasing slightly.

Table 12. *Collision, grounding, and contact accidents recorded by EMSA 2018-2022.*

	2018	2019	2020	2021	2022	Average
Collision	494 (21,9%)	564 (23,1%)	370 (16,8%)	441 (18,9%)	383 (17,4%)	450,4 (19,7%)
Contact	323 (14,3%)	343 (14,1%)	328 (14,9%)	344 (14,7%)	323 (14,7%)	332,2 (14,5%)
Grounding	266 (11,8%)	243 (10%)	229 (10,4%)	251 (10,7%)	207 (9,4%)	239,2 (10,5%)
Total number of occurrences	2255	2440	2196	2332	2198	2284,2

Note: The information in this table is gathered from the publication "Annual Overview of Marine Casualties and Incidents 2023" by the European Maritime Safety Agency (2023, October 27). https://www.emsa.europa.eu/publications/reports/item/5052-annual-overview-of-marine-casualties-and-incidents.html

Antão et al (2023) investigated the distribution of accident types within a sample collected from the accidents reported to the IMO between the years 2005-2017 and found that collision was the most common accident type, and that grounding accidents came in second place. Contact was the eighth most common accident type within the sample. The results are presented in table 13.

Table 13. *Distribution of the relevant accident types reported to the IMO 2005-2017.*

Type of accident	Number of accidents	Percentage of accidents
Collision	936	19,7%
Grounding	768	16,2%
Contact	251	5,3%
Other	2797	58,9%

Note: The information in this table is gathered from the article "Quantitative Assessment of Ship Collision Risk Influencing Factors from Worldwide Accident and Fleet Data" by Antão, P., Sun, S., Teixeira, A.P., & Guedes Soares, C. (2023). *Reliability Engineering & System Safety.* Volume 234. https://doi.org/10.1016/j.ress.2023.109166

The total number of accidents in the sample is N = 4752. The accident scenario statistics from the article by Antão et al. (2023) that were not relevant to this report have been excluded from the table.

Endrina et al (2018) conducted a report concerning risk analyses of RoPax ships in the Strait of Gibraltar. The estimated number of ship movements in the area is 110.000 per year, out of which approximately 33% is made by RoPax ships. When doing the frequency analysis, they made calculations based on both frequency per ship year and frequency per ship movement. They argue that it is more suitable to calculate the frequency based on ship movements, as ships that complete a larger number of journeys face a greater risk of being involved in an accident.

The actual values that Endrina et al (2018) used when carrying out the frequency analysis of different scenarios, as well as the results thereof, are presented below in table 14. The calculations are based on the number of ship movements in the Strait of Gibraltar between the years of 2000-2011, when 1.170.120 movements were recorded in total. Those statistics were provided to the authors by the Spanish Maritime Safety Agency. Out of the total number of ship movements, 383.213 of them were estimated to have been made by RoPax ships. Endrina et al (2018) found that the RoPax ships are statistically more likely to be involved in a ship collision than other types of vessels, which can be seen on the right side of table 14.

Table 14. *Overview of accident frequency analysis results.*

Ship type	All Ships (including RoPax ships)	
Accidents	Number	Frequency
Accident type		
Collision	14	1,2 x 10^{-5}
Grounding	9	7,7 x 10^{-6}
Contact	6	5,13 x 10^{-6}

Note: The information in this table is gathered from the article "Risk Analysis of RoPax vessels: A Case of Study for the Strait of Gibraltar" by Endrina, N., Rasero, J.C., & Konovessis, D. (2018). *Ocean Engineering.* Volume 151. 141-151. https://doi.org/10.1016/j.oceaneng.2018.01.038

The total number of ship movements during the period was N = 1.170.120.

The results from the report by Endrina et al. (2018) that were not relevant to this report have been excluded from the table.

Antão et al. (2023) writes that the growing fleet of the maritime industry will increase ship traffic, and in doing so the probability of ship collisions is also likely to increase. They found statistics from the IMO that approximately 20% of all accidents reported to them are ship collisions.

4.3 Statistics and Simulations on Ship Damage

When collisions, contact, or grounding occurs, there will be damage done to the ship or ships involved. The amount of damage sustained by the parties can vary greatly depending on ship speed, the area of the ship that is struck, and if the ship strikes something or is being struck. Pilatis et al. (2024) conducted a statistical analysis of world-wide ship casualties between the years of 1990 and 2020. They reviewed more than a thousand casualty reports to create a sample of 213 casualties involving collision, grounding, and structural failure. The information of the marine accidents was compiled to give an indication of which part of the ship is statistically more likely to receive more damage. They could also determine how deep into the ship that damage went statistically.

4.3.1 Collision Damage

Collision damage is the damage that is delt to a ship, either the striking ship or the struck ship, in a collision accident. The locations of the damage and the extent of it is presented in this section. All the percentages and numbers presented in this section are based on statistics.

Longitudinal Location of Damage

The percentages of longitudinal collision damage location in the article by Pilatis et al (2024) clearly demonstrates that the bow and the area surrounding it is most likely to receive damage in a collision, as the two most forward parts represent more than half of all recorded damage in this scenario. The damage location statistics are shown in table 15. The ships length between the perpendiculars is divided into ten equal parts each representing 10% of the length, with 0%

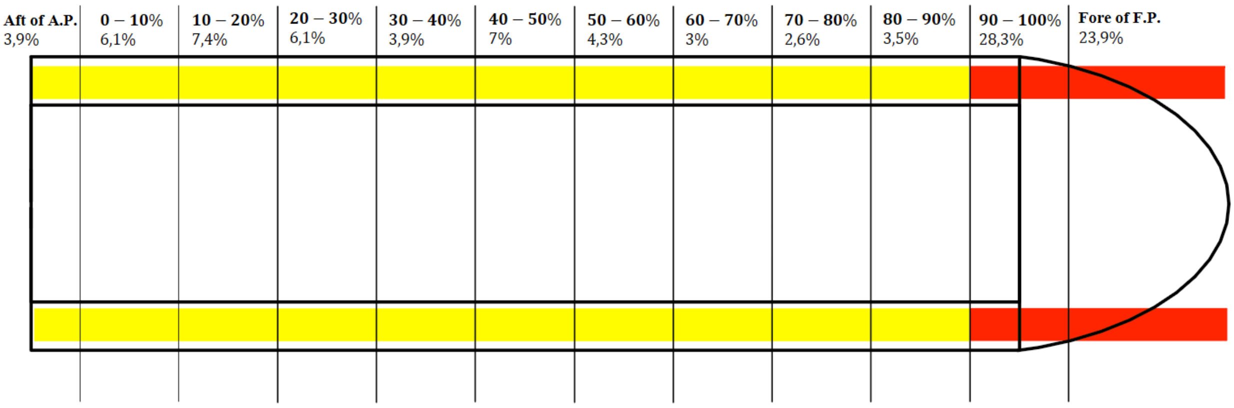
at the aft perpendicular and 100% at the forward perpendicular. The percentages from table 15 are presented visually in figure 5.

Table 15. *Longitudinal collision damage location.*

Location of damage	Percentage of casualties
Aft of A.P.	3,9%
0-10 %	6,1%
10-20%	7,4%
20-30%	6,1%
30-40%	3,9%
40-50%	7%
50-60%	4,3%
60-70%	3%
70-80%	2,6%
80-90%	3,5%
90-100%	28,3%
Fore of F.P.	23,9%

Note: The information compiled in this table is gathered from the article "A Statistical Analysis of Ship Accidents (1990-2020) Focusing on Collision, Grounding, Hull Failure, and Resulting Hull Damage" by Pilatis, A.N., Pagonis, D.N., Serris, M., Peppa, S., & Kaltsas, G. (2024). Journal of Marine Science and Engineering, 12(1), p. 122. https://doi.org/10.3390/jmse12010122
A.P signifies the Aft Perpendicular, and F.P signifies the Forward Perpendicular.

Figure 5. *Longitudinal collision damage location*



Note: The information in this figure is based on the information from table 15. The red colour represents the area that is most likely to receive damage in a collision.

Vertical Location of Damage

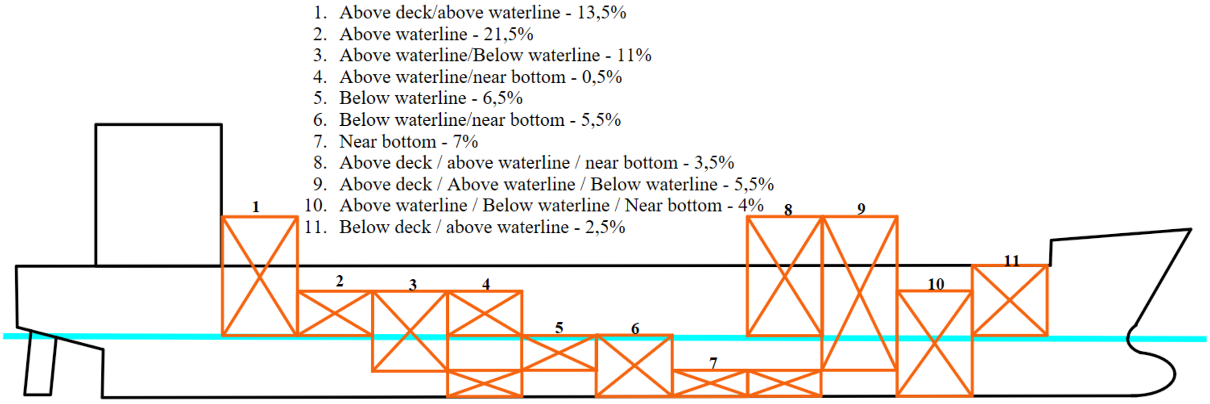
The vertical location of damage is determined by at which height of a ship's side the damage is delt. The statistics that Pilatis et al (2024) found on this damage location are presented in table 16 and visualised in figure 6. The damage that happened in one single area has one percentage, and damages that happened in a combination of areas have their own percentage. They found that the areas above the waterline are most likely to be damaged in a collision, and that they make out more than 50% of all vertical damage locations.

Table 16. *Vertical collision damage location.*

Location of damage	Percentage of casualties
Above deck	19%
Above deck/above waterline	13,5%
Above waterline	21,5%
Above waterline/Below waterline	11%
Above waterline/near bottom	0,5%
Below waterline	6,5%
Below waterline/near bottom	5,5%
Near bottom	7%
Above deck / above waterline / near bottom	3,5%
Above deck / Above waterline / Below waterline	5,5%
Above waterline / Below waterline / Near bottom	4%
Below deck / above waterline	2,5%

Note: The information compiled in this table is gathered from the article “A Statistical Analysis of Ship Accidents (1990-2020) Focusing on Collision, Grounding, Hull Failure, and Resulting Hull Damage” by Pilatis, A.N., Pagonis, D.N., Serris, M., Peppa, S., & Kaltsas, G. (2024). Journal of Marine Science and Engineering, 12(1), p. 122. https://doi.org/10.3390/jmse12010122

Figure 6. *Vertical location of damage*



Note: The information in this picture is gathered from table 16. The orange boxes that contain an ‘X’ are a visualisation of the area the number above it represents.

Transverse Damage Extent

Transverse damage extent is how far the damage reaches into the side of the ship in a horizontal direction.

Liu et al. (2021) used statistical values to find how much energy is absorbed as a ship collides with another ship. They found the median value of the absorbed energy to be 30,3 MJ, and the 90-percentile to be 152,3 MJ. These absorbed energies correspond to different penetration depths into the hull, and they also differ depending on if the striking ship has a bulbous bow or a straight bow. The top of the straight bow was the part of the stem that extended the farthest forward in that model, and in the other model the tip of the bulbous bow in the extended farther forward than the top of the stem. The results were as shown in table 17. The authors point out that the damage delt by the ship with the straight bow to the struck ship could be more severe if it had occurred to a ship with less torsional and longitudinal strength, as well as if the struck ship had had more of a superstructure than the model ship had.

Table 17. *Hull penetration depth depending on bow type.*

Absorbed energy Bow type	30,3 MJ (median)	152,3 MJ (90-percentile)
Bulbous bow	2,33m	3,9m
Straight Bow	1.31m	2,67m

Note: The information in this table was gathered from the article "Analysis of Structural Crashworthiness of Ships in Collision and Grounding" by Liu, B., Villavicencio, R., Terndrup Pedersen, P., & Guedes Soares, C. (2021) *Marine Structures.* Volume 76. https://doi.org/10.1016/j.marstruc.2020.102898 The penetration depth into the struck ship varies depending on the bow shape that the striking ship has.

Liu et al (2021) found that the ship with the straight bow did not penetrate the steel structure of the struck ship at any of the energy scenarios, only deformed it. That was not the case when the bulbous bow was tested, as the 30,3 MJ scenario led to the outer hull being penetrated, and both hulls were penetrated in the 152,3 MJ scenario. The distance between the inner and outer hull was 2,1 meters.

Liu (2017) conducted a similar simulation test, where a bulbous bow and simplified shapes that could represent the shape of a bulbous bow collided with the side of a double-hulled ship. The results of the deformation of the hull when struck by the bulbous bow were that the initial crack in the outer hull appeared after absorbing roughly 30 MJ of energy and at a penetrating deformation of approximately 1,15 meters, and the outer hull ruptured thereafter, at a penetration depth of approximately 1,2 meters.

4.3.2 Grounding Damage

Grounding damage is the damage that is delt to a ship when it drifts or runs into a natural obstacle such as the sea bottom or shore, or when it strikes underwater wrecks.

Vertical Damage Extent

Liu et al (2021) observed that the median vertical damage depth done to a ship when grounding was 1.13 meters, and at the 90-percentile value for the same event the damage depth was 2,63 meters, based on statistical data calculated as the product of the ship's depth and the ratio between the grounded depth and the ship depth. They noted that none of those damage depths were enough to rupture the bottom of the hull in the stranding simulation.

Transverse Location and Damage

The statistics in table 18 from Pilatis et al (2024) shows that the area close the centreline and keel is the most likely place to be damaged in a grounding scenario, followed by the sides of the hull. This result is markedly different from the statistics that Liu et al (2021) found, which was that grounding often occurs at the midway point between the ship's keel and the side of the ship.

Table 18. *Transverse grounding damage location.*

Location of damage	Percentage of casualties
42-50% (Starboard)	8,2%
33-42%	10%
25-33%	7,4%
17-25%	6,6%
8-17%	6,1%
0-8%	11,8%
Centreline (0%)	12,4%
0-8%	10,5%
8-17%	5,3%
17-25%	3,9%
25-33%	5,8%
33-42%	7,4%
42-50% (Port)	4,7%

Note: The information compiled in this table is gathered from the article "A Statistical Analysis of Ship Accidents (1990-2020) Focusing on Collision, Grounding, Hull Failure, and Resulting Hull Damage" by Pilatis, A.N., Pagonis, D.N., Serris, M., Peppa, S., & Kaltsas, G. (2024). Journal of Marine Science and Engineering, 12(1), p. 122. https://doi.org/10.3390/jmse12010122

The damage extent into the side of the ship from a grounding scenario that Pilatis et al (2024) found is presented in table 19a and 19b. They found that approximately 75% of the damage extends no more than 2,5m into the ship in the transverse direction, as can be seen it table 19. There were however some cases where the damages went much deeper into the ship however, the extreme damage depth being 20-30 meters. The largest percentages of damage with a depth greater than 2,5 meters was 3-4 meters deep in 6% of the accidents, and 8-10 meters deep in 5,3% of the accidents.

Table 19 a. *Transverse damage extent due to Grounding.*

Depth of damage	0 – 0,5 m	0,5 – 1m	1 – 1,5m	1,5 -2m	2 – 2,5 m	> 2,5 m
Percentage of casualties	7,3%	8%	14,7%	18,7%	26,7%	24,6%

Note: The information compiled in this table is gathered from the article "A Statistical Analysis of Ship Accidents (1990-2020) Focusing on Collision, Grounding, Hull Failure, and Resulting Hull Damage" by Pilatis, A.N., Pagonis, D.N., Serris, M., Peppa, S., & Kaltsas, G. (2024). Journal of Marine Science and Engineering, 12(1), p. 122. https://doi.org/10.3390/jmse12010122

Table 19 b. *Transverse damage extent due to Grounding continued.*

Depth of damage	2,5 – 3 (m)	3 - 4 (m)	4 – 5 (m)	5 – 6 (m)	6 – 7 (m)	7 – 8 (m)	8 – 10 (m)	10 – 15 (m)	15 – 20 (m)	20 – 30 (m)
Percentage of casualties	2%	6%	0,7%	4%	0,7%	2%	5,3%	2,7%	0%	1,3%

Note: The information compiled in this table is gathered from the article "A Statistical Analysis of Ship Accidents (1990-2020) Focusing on Collision, Grounding, Hull Failure, and Resulting Hull Damage" by Pilatis, A.N., Pagonis, D.N., Serris, M., Peppa, S., & Kaltsas, G. (2024). Journal of Marine Science and Engineering, 12(1), p. 122. https://doi.org/10.3390/jmse12010122

Longitudinal Location and Damage

The results from Pilatis et al (2024) are presented in table 20, and they show that the aft half of the ship is slightly more likely to be damaged during a grounding accident than the forward half, with their respective percentages being 57,6% and 42,4%. The most represented longitudinal grounding location is the bow however, where 21,5% of all damage occurs. They draw the conclusion that the bow area is damaged the most in both collision and grounding scenarios, and that in grounding scenarios, the majority of the vessels were damaged in the centreline area and the areas closest to the side of the hull. They also deduce that damages below the waterline had an increased risk of leading to a total loss of the vessel, compared to damages above the waterline, which were often repaired.

Table 19. *Longitudinal grounding damage location.*

Location of damage	Percentage of casualties
Aft of A.P.	11,3%
0-10 %	2,7%
10-20%	9,7%
20-30%	10,8%
30-40%	12,9%
40-50%	10,2%
50-60%	6,5%
60-70%	5,9%
70-80%	3,2%
80-90%	5,4%
90-100%	18,8%
Fore of F.P.	2,7%

Note: The information compiled in this table is gathered from the article "A Statistical Analysis of Ship Accidents (1990-2020) Focusing on Collision, Grounding, Hull Failure, and Resulting Hull Damage" by Pilatis, A.N., Pagonis, D.N., Serris, M., Peppa, S., & Kaltsas, G. (2024). Journal of Marine Science and Engineering, 12(1), p. 122. https://doi.org/10.3390/jmse12010122

4.4 Battery Information

Information found regarding statistics on deformation of batteries will be found in this section, along with guidelines and information on battery safety.

4.4.1 Battery Statistics

Wang et al (2022) write that failures of lithium-ion batteries are mainly caused by various kinds of abuse, and that mechanical abuse in the form of deformation, puncture, and collapse is the most prevalent cause of failures, and that it will affect the safety of the battery.

Wang et.al (2022) found that cylindrical lithium-ion type battery cells with a length of 65mm and diameter of 18mm (also known as an 18,650 battery) could only be compressed about 2.3mm when axially compressed before the cell either lost voltage or a thermal runaway occurred, depending on the cell's state of charge. Radial deformation along the entire length of the battery fared better, reaching 3.36 mm before the cell was affected in a negative way.

Deformation of the same type of cylindrical battery cell that Wang et al (2022) examined was also tested by Voyiadjis et al (2023) by using a cylindrical indenter with a diameter of 16mm, and they found that a cylindrical battery cell could be radially compressed approximately 6,2 mm with the indenter laying on its side before an internal short circuit occurred.

Spielbauer et al (2019) found that the indentation depths that an 18,650 cylindrical battery could withstand before an internal short circuit occurred not only varied with the shape of the indenter, but also with the state of charge of the battery, with a higher state of charge leading to internal short circuiting at a shallower indentation depth. The results can be seen in table 21.

Table 20. *Depths reached when a short circuit of the cylindrical battery cell occurred.*

Indenter	Nail (ø = 3mm)	Cylinder (ø = 20mm)	Hemisphere (ø = 5mm)
State of charge			
100%	1,8mm	8,4mm	6,4mm
50%	2,2mm	8,2mm	6mm
0%	2mm	9,2mm	6,6mm
Average	2mm	8,6mm	6,3mm

Note: The information in this table is gathered from the article "Experimental Study of the Impedance Behaviour of 18650 Lithium-ion Battery Cells under Deforming Mechanical Abuse" by Spielbauer, M., Berg, P., Ringat, M., Bohlen, O., & Jossen, A. (2019). Journal of Energy Storage, volume 26. https://doi.org/10.1016/j.est.2019.101039

Moon et al. (2022) found that indenters of different shapes could indent a battery cell pouch with a thickness of 4,6 mm approximately 2,9 mm before an internal short circuit occurred. The results are presented in table 22. They also found that sharper indenters could penetrate farther into the pouch cell before an internal short circuit occurred and reasoned that this was because the sharper indenter creates a smaller area that can short circuit. The indenter with the largest radius (a cylinder) caused a short circuit at a slightly shallower depth than the other indenters, and it also generated the largest voltage drop, the highest short circuit current, and the highest temperature of the three indenter types. This was because it created the largest area of failed separator, which also causes less electric resistance.

Table 21. *Indentation limits of different indenters on a pouch battery cell.*

Indenter type	Cylindrical (ø = 6,35mm)	Hemispherical (ø = 12,7 mm)	Conical (120°)
Limit	2,85mm	2,9mm	2,96mm

Note: The information in this table is gathered from the article "Prediction of Internal Circuit and Mechanical-Electrical-Thermal Response of Lithium-ion Battery Cell with Mechanical-Thermal Coupled Analysis" by Moon, J., Chang, H., Lee, J., & Kim, C.W. (2022). Energies, 15(3), 929. https://doi.org/10.3390/en15030929

The experiment conducted by Newaz et al (2020) reached results similar to those of Moon et al, as a hemispherical indenter with a diameter of 6,35mm reached a depth of approximately 2,9mm into a pouch battery cell before a complete short circuit occurred.

Kisters et al (2017) indented a pouch battery cell with a hemispherical indenter with a diameter of 12,7mm, and found that the voltage of the cell did not drop until it was punctured, and even then, the voltage did not drop all the way to zero. At some puncturing velocities the voltage decreased gradually, and at others it decreased sharply. At an impact velocity of 5 m/s, the voltage gradually decreased at an indentation depth of approximately 2,5mm, and when the velocity was 33 cm/s the voltage dropped rapidly at an indentation depth of approximately 4,5mm.

Qin et al (2023) conducted an experiment on prismatic batteries with the dimensions 148 x 91 x 26,5mm under compression and monitored the voltage during the test. They tested the battery in four different ways and found that compressing the entire cell in the directions of the dimensions did not lead to a short circuit, only the test of local compression using a cylindrical indenter with a diameter of 50mm led to a decrease in voltage, which indicates a short circuit within the battery. They also found that the deformed area of the battery cell decreased with an increased impact speed, and the damage becomes more localised. However, with increased impact velocity, the possible displacement before a critical failure occurs decreases. When the velocity was less than 1 m/s, the displacement reached 8,1mm before the critical failure happened, but when the velocity exceeded 14 m/s, the critical failure appeared at a displacement of approximately 4,5 mm.

The experiment performed by Kisters et al (2017) yielded similar results as those of Qin et al (2023). When elliptical prismatic lithium-ion cells were impacted by a hemispherical indenter with a diameter of 12,7mm, they found that the depth of indentation varied with the velocity of the impact, and that a higher impact velocity induced an internal short circuit at a shallowed indentation depth than a lower velocity impact would. At an impact speed of 5 m/s, the indenter reached a depth of roughly 5,2mm before a rapid decrease of voltage occurred, and the same value for an impact speed of 1 mm/s was roughly 6mm. At even slower impact speeds, the indentation depth was slightly lower than 5mm when the internal short circuit occurred. The behaviour of the voltage drop for the elliptical cell was the same as for the pouch cell, with some drops occurring rapidly, and others gradually.

4.4.2 Battery Safety, Guidelines, and Common Practice

Chombo et al (2021) explain that all the potential consequences related to the abuse and deformation of a battery is a driving factor for researchers to investigate crashworthiness of battery vehicles. They write that the battery pack in electric vehicles are placed in reinforced areas of the vehicle, so that most collision scenarios will not cause damage to the battery pack. It is also common practice to not place the pack in the impact zones of the vehicle, with the goal of reducing the risk of deformation in an accident. They conducted multiple crash tests of various electric vehicles suggest that the method used to protect the battery pack is effective, as no obvious damage of the pack was observed.

Bisschop et al (2019) also stated that placing the batteries of electric vehicles in reinforced compartments is a method to protect the batteries from being damaged in a collision. They can also be placed in areas that are less prone to be affected in a collision, something that is referred to as the “safe zone”. That zone is generally around the centre of the vehicle, some distance in from the sides of the vehicle and not extending in front of the front wheel axle or further back than the back wheel axle. The way that the battery pack is arranged within that area can vary, and each arrangement has its own pros and cons.

Trombetta et al (2024) state that one of the most important aspects when choosing batteries for maritime use is safety, both because of the potential risks associated with batteries, and because there are quite few large battery systems in use onboard ships, and thereby there are not enough practical sailing tests done yet.

Trombetta et al (2024) further explain how battery dimensions on board ships can be limited by available space or weight. In addition to this, the battery space must follow classification rules, and the classification society Det Norske Veritas states that the battery spaces onboard ships classed by them need to be constructed in such a way that they are protected from external hazards such as mechanical impact (Mjøs et al, 2016). They further stated that the placement of a battery space onboard a vessel must be thoroughly considered and planned in such a way as to reduce the risk of it being affected by external events. It is explicitly stated that a battery space cannot be located forward of the forward collision bulkhead.

4.5 Compilation and Calculation of Statistics

The calculations made using the numbers gathered from the statistics presented in sections 4.2 - 4.4 this chapter will be presented here, and they will be explained further and used to determine the frequency and severity of accidents in the Discussion chapter.

4.5.1 Accidents Per Port Call

The statistics presented in chapter 4.2.1 in tables 7-9 are presented in table 23 and gives an overview of the statistics on the number of accidents per port call in a certain area. The number of accidents and the number of port calls from the different sources are first displayed separately, and in the last row they are calculated in such a way as to give and average number of accidents per port call within the specified area.

Table 22. *Data found regarding port calls and accidents within a specific area.*

Part of world	Sweden	Europe	Baltic sea
Source	Swedish Transport Agency (2023)	EMSA (2023, October 27) and Eurostat (2023)	Sormunen et al (2016)
Information from table no.	7	5, 6	8, 9
Port calls (average)	10.000	2.127.578,4	480.631
Accidents reported	9,4 (average)	2649,4 (average)	653
Accidents per port call	9,4 x 10^{-4}	1,25 x 10^{-3}	13,6 x 10^{-3}

Note: The information in this table is compiled from the tables 5-9 in chapter 4.2.1. The numbers in the row "accidents per port call" represent the likelihood of a ship experiencing an accident for every port call it makes in a certain area.

The numbers from the bottom row (Accidents per port call) of table 23 are added together in calculation 1 to give an overall average of the number of accidents per port call.

Calculation 1: *Average on accidents per port call.*

$$\frac{(9,4 * 10^{-4}) + (1,25 * 10^{-3}) + (13,5 * 10^{-3})}{3} \approx 5,26 * 10^{-3}$$

Note: The numbers in the equation are from table 23, and they are used to get an overall average value of the number of accidents per port call.

4.5.2 Distribution of Accident Types

The statistics presented in chapter 4.2.3 in tables 11-13 are presented in table 24 and gives an overview of the statistics on the distribution of the accident types collision, grounding, and contact in a certain area. The average percentages of the accident types from the different sources are first displayed separately, and the overall average percentage on each accident type is presented in the last column.

Table 23. *Data found regarding the distribution of accidents within a specific area.*

Source	Swedish Transport Agency (2023)	EMSA (2023, October 27)	Antão et al.	Average
Part of world	Sweden	Europe	Global	-
Information from table no.	11	12	13	-
Collision (average)	11,4%	19,7%	19,7%	16,93%
Grounding (average)	16,3%	10,5%	16,2%	14,3%
Contact (average)	14,3%	14,5%	5,3%	11,37%

Note: The information in this table is gathered from tables 11-13 in chapter 4.2.3. The column farthest to the right presents the combined average percentage of each accident type.

The average percentages of the accident types collision, grounding, and contact from table 24 are converted to decimals, and they are then multiplied with the likelihood of a ship experiencing an accident per port call from calculation 1 to determine the likelihood of a ship experiencing each accident type per port call. The process in shown in calculation 2.

Calculation 2: *The likelihood of a ship experiencing the accident types per port call.*

$$\text{Collision: } 5{,}26 * 10^{-3} * 0{,}1693 \approx 8{,}9 * 10^{-4}$$
$$\text{Grounding: } 5{,}26 * 10^{-3} * 0{,}143 \approx 1{,}27 * 10^{-4}$$
$$\text{Contact: } 5{,}26 * 10^{-3} * 0{,}1137 \approx 5{,}98 * 10^{-4}$$

Note: The result from calculation 1 is used in combination with the average percentages of each accident type presented in table 24.

4.5.3 Battery Damage Statistics

The damage delt to the battery cells before they experienced a short circuit are compiled in tables 25-27. Table 25 displays the indentation limits for cylindrical cells, table 26 displays the limits for pouch cells, and table 27 displays the limits for prismatic cells.

The limits in table 25 shows that the shallowest indentation depth that can lead to an internal short circuit is 2mm, and the deepest is 8,6mm, for cylindrical batteries.

Table 24. *Overview of deformation data on cylindrical battery cells.*

Source	Table / Section	Indenter type	Direction	Limit
Wang et al (2022)	Section 4.4.1	Compression (flat)	Axial	2,3mm
Wang et al (2022)	Section 4.4.1	Compression (flat)	Radial	3,36mm
Voviadjis et al (2023)	Section 4.4.1	Cylindrical (ø = 16mm)	Radial	6,2mm
Spielbauer et al (2019)	Table 21 Section 4.4.1	Nail (ø = 3mm)	Radial	2mm (average)
Spielbauer et al (2019)	Table 21 Section 4.4.1	Cylindrical (ø = 20mm)	Radial	8,6mm (average)
Spielbauer et al (2019)	Table 21 Section 4.4.1	Hemispherical (ø = 5mm)	Radial	6,3mm (average)

Note: The information in this table is gathered from chapter 4.4.1 and table 21. Compression means that the cell ins compressed all over its topmost surface area.

The statistics on pouch batteries in table 26 shows that the results vary slightly with indentation speed and the shape of the indenter, but that the results overall are close to 3mm.

Table 25. *Overview of deformation data on pouch battery cells.*

Source	Table / Section	Indenter type	Direction	Limit
Moon et al (2022)	Table 22 Section 4.4.1	Cylindrical (ø = 6,35mm)	Vertical on flat side	2,85mm
Moon et al (2022)	Table 22 Section 4.4.1	Hemispherical (ø = 12,7mm)	Vertical on flat side	2,9mm
Moon et al (2022)	Table 22 Section 4.4.1	Conical (120°)	Vertical on flat side	2,96mm
Newaz et al (2020)	Section 4.4.1	Hemispherical (ø = 6,35mm)	Vertical on flat side	~2,9mm
Kisters et al (2017)	Section 4.4.1	Hemispherical (ø = 12,7mm)	Vertical on flat side	~2,5mm (5 m/s) ~4,5mm (33 cm/s)

Note: The information in this table is gathered from chapter 4.4.1 and table 22.

The combined overall average indentation limit of a pouch cell being deformed is presented in calculation 3.

Calculation 3: *Overall average indentation depth of pouch battery cells.*

$$\frac{2{,}85 + 2{,}9 + 2{,}96 + 2{,}9 + 2{,}5 + 4{,}5}{6} = 3{,}1mm$$

Note: These numbers in this calculation are gathered from table 26.

The limits in table 27 show that the shallowest indentation depth leading to a short circuit is 4,5mm, and the deepest is 8,1mm. It also shows that Cuboid prismatic battery cells can be compressed farther before a voltage drop occurs than they can be indented.

Table 26. *Overview of deformation data on prismatic battery cells.*

Source	Table / Section	Cell shape	Indenter type	Direction	Limit (indentation speed)
Qin et al (2023)	Section 4.4.1	Cuboid	Compression (flat)	Through thickness (26,5mm)	>7mm
Qin et al (2023)	Section 4.4.1	Cuboid	Compression (flat)	Through Length (148mm)	>20mm
Qin et al (2023)	Section 4.4.1	Cuboid	Compression (flat)	Through Breadth (91mm)	>10mm
Qin et al (2023)	Section 4.4.1	Cuboid	Cylindrical (ø = 50mm)	Through thickness (26,5mm)	8,1mm (1 m/s) 4,5mm (14 m/s)
Kisters et al (2017)	Section 4.4.1	Elliptical	Hemispherical (ø = 12,7mm)	Through thickness (18mm)	~5,2mm (5 m/s) ~6mm (1 mm/s)

Note: The information in this table is gathered from chapter 4.4.1.

5. DISCUSSION

The results and calculations from the Results chapter are used to evaluate the risks a ship can be exposed to, the frequency of the accidents, and the severity of the damage. The results from chapter for are then used in combination with the result from the risk assessment to evaluate which areas of a ship is better suited to contain batteries. The outcome of the risk assessment is discussed, as well as the method behind the report, and the challenges that were encountered during the writing process.

5.1 Battery Resilience and Fire Safety

The results from chapter 4.4.1 indicate that very little deformation is needed in order for a battery to experience a voltage drop and thereby also a short circuit, in all cases the deformation was measured in millimetres which shows how sensitive the battery cells really are and also that there is a need to both protect them in casings and also place them where the risk of damaging them can be considered acceptable. Det Norske Veritas came to the same conclusion regarding placement of batteries as shown in chapter 4.3.2. Looking into how much a battery can deform before thermal runaway occurs it was found that several independent sources came to very similar conclusions showing that the data used is valid.

To avoid mechanical abuse of batteries is an integral part of preventing fires and thereby making electric vehicles and vessels safe for use by humans.

5.2 Risk Analysis

To conduct a Formal Safety Assessment as presented in chapter 2.4, the accident scenarios need to be identified, and the risks need to be assessed. The frequency and severity of the accident scenarios are an essential part of the risk assessment, the frequency is based on the percentages and numbers presented in chapters 4.5.1 and 4.5.2, and the severity is based on the percentages and numbers presented in chapter 4.3.

5.2.1 Identification of Accident Scenarios

The accident types that are relevant for this report are those that can lead to damage of the ship structure, particularly the hull, since damage that extends deep into the hull pose a risk to potential batteries that could be placed there. Those scenarios have been identified as collision, grounding, and contact accidents, as they are defined in chapter 4.2.3.

5.2.2 Accident Frequency

The frequencies of collision, grounding, and contact calculated in chapter 4.5.2 calculation 2 indicate the likelihood of a ship experiencing any of those accident types for every port call or journey that a ship makes. As is stated in chapter 4.2.3 by Endrina et al (2018), there is a higher risk of experiencing an accident when the ship is regularly completing sea journeys, compared to when it is laying still.

The results from calculation 2 in chapter 4.5.2 shows that the magnitude of the likelihood of the various accident scenarios is 10^{-4}. The results from calculation 2 can be compared somewhat to the numbers presented by Endrina et al (2018) in table 14 in chapter 4.2.3, as they determined the likelihood of collision, grounding, or contact per ship movement to be in the magnitude of 10^{-5} – 10^{-6}. The difference in magnitude is possibly because a ship movement does not necessarily mean that a ship makes a port call within the area, and thereby might not get as close to shore and shallower waters as ships that makes port calls. This makes is a bit difficult to fairly compare the results from calculation 2 and table 14. The magnitude of 10^{-4} gives the accidents a frequency index of 2 in accordance with table 28.

Table 27. *Frequency Index table*

Frequency index	Frequency	Definition	F (Per port call)
7	Frequent	Likely to occur once per month on a ship	10
6			
5	Reasonably probable	Likely to occur a few times during a ship's lifetime	0,1
4			
3	Remote	Likely to occur once in a ship's lifetime	10^{-3}
2			
1	Extremely remote	Not likely to occur even once in a ship's lifetime	10^{-5}

Note: The information in this table is based on the frequency index table in the publication "Revised Guidelines for Formal Safety Assessment (FSA) for use in the IMO Rule-Making Process (MSC-MEPC.2/Circ12/Rev.2)" by the International Maritime Organisation. (2018, April 9). https://wwwcdn.imo.org/localresources/en/OurWork/HumanElement/Documents/MSC-MEPC.2-Circ.12-Rev.2%20-%20Revised%20Guidelines%20For%20Formal%20Safety%20Assessment%20(Fsa)For%20Use%20In%20The%20Imo%20Rule-Making%20Proces...%20(Secretariat).pdf
Some of the definitions have been altered to better suit this report, and the numbers have been changed from "per ship year" to "per port call". IMO defines a ships lifetime as 20 years, and therefore the definition is the same in this table.

5.2.3 Initial Accident Severity

The severity of the collision and grounding scenarios are based on the simulation and statistical data presented in chapter 4.3.1 and 4.3.2. In this first accident severity rating scenario, there are batteries are placed in the spaces that normally makes up the double hull, namely closer to the outer hull than 2 meters, as it is the upper limit of the distance between double hulls recommended by MARPOL when transporting oil cargo (table 1 chapter 2.5). If the batteries are deformed in an accident, there is an evident risk of an internal short circuit occurring, which in turn leads to a risk of fire that cannot be ignored or underestimated.

Collision

The percentages in table 15 shows that the risk of damage in a collision is higher in the forward part of the ship, specifically in the area around the forward perpendicular, where more than 50% percent of the damages happen. The bow is naturally more likely to be damaged when the ship is striking another ship. The area between the aft perpendicular and the halfway point of the ship's length also face a higher risk of being damage in a collision, and it represents 30,5% of the damage of all collision scenarios. This could be because the striking ship attempts to steer away from the ship in the collision path but does not manage to do so completely before the collision occurs.

How far the damage extends transversely into the side of the ship when it has been struck depends on the shape of the bow on the striking ship, as well as how much energy the struck ship will need to absorb to stop the striking ship. The information in table 17 shows that the median damage depth delt to the struck ship is deeper than the minimum double hull distance recommended by MARPOL in table 1, and it is also often deeper than the largest distance demanded by them. Liu (2017) describes in chapter 4.3.1 that a hull deformed approximately 1,15m before a crack appeared, which is within the 2-meter upper limit recommended by MARPOL. One of the penetration depths presented in table 17 also fall within the 2-meter limit, but the other three damage depths are deeper than 2 meters.

This means that the damage done in a collision is likely to transversely extend farther into the ship than the recommended double hull distances. Those penetration depths would almost certainly deform any battery pack in the immediate impact area and cause one or several short circuits within the batteries, which can lead to thermal runway and fires that are difficult to extinguish, as presented in chapter 2.1.2. The severity of collision damage is therefore evaluated to the severity index 4 in accordance with table 29.

Grounding

The percentages in table 20 shows that the aft half of the ship receives 57,6% of all grounding damage, but that the bow of a ship alone receives more than 21% of all grounding damage. These areas represent 77,1% of all the damage locations on a ship. The bow is likely to be the first area that impacts on a rock or other natural obstacle, but the trim of the ship can influence which part of the hull that is damaged.

The information in table 18 shows that the keel/centreline and the transverse area immediately next to it has the highest likelihood of being damaged in a grounding scenario, and their combined likelihood of damage is almost 35%. The reason behind this could be that the keel of the ship often is the lowest point of the hull and is therefore more likely to hit obstacles under the ship.

The transverse damage extent into the side of the ship is shown in table 19a, and it shows that 75% of the damage does not extend farther than 2,5m into the ship’s side. These values can be compared to the transverse damage extent delt to a ship in a collision scenario, as they are quite similar. The vertical damage extent into the bottom of the hull observed by Liu et al (2021) in chapter 4.3.2 showed that 90% of the damages extended less than 2,63 meters vertically into the ship, and that those damage depths were not enough to rupture the hull, only deform it. However, table 19b shows that there are some accidents that result in damages much deeper than 2,5 meters, in some cases even as deep as 20-30 meters.

These findings indicate that the damage depth delt to a ship as a consequence of grounding most likely is less than approximately 2,63m, and that those deformations do not necessarily lead to a rupture of the hull. The deformation depth is still likely to be greater than the 2-meter upper limit hull distance recommended by MARPOL in table 1, and such a damage depth would impact the batteries in the same way as stated above in the Collision scenario. The severity of grounding damage is therefore evaluated to the severity index 4 in accordance with table 29.

Contact

As there were no damage statistics found on the consequences of a contact accident, it is difficult to establish a basis for the extent of damage that can be delt to a ship in such a scenario. A contact per the definition in chapter 4.2.3 is a scenario where a ship can strike any object other than another ship, natural obstacles, or wrecks, which means that the actual accident scenarios can be very different from each other. They can range from bumping into the quay when berthing or running over a buoy, to colliding with a bridge or other large structure. This means that the consequent damages of a contact scenario can vary from minor damages to severe or even catastrophic. With no sources found on the damage extent of contact, the Severity Index is determined to be 1 in accordance with table 29.

Table 28. *Severity Index table*

Severity index	Severity	Effects on ship	S (Equivalent fatalities)
1	Minor	Local equipment damage: no down-time needed for repairs	0,01
2	Significant	Non-severe ship damage: does not compromise the safety of the ship, down-time may be needed for repairs	0,1
3	Severe	Severe Damage: compromises buoyancy or safety of the ship, repairs are essential	1
4	Catastrophic	Total loss: abandon ship, ship sinking, or not worth repairing	10

Note: The information in this table is based on the severity index table in the publication "Revised Guidelines for Formal Safety Assessment (FSA) for use in the IMO Rule-Making Process (MSC-MEPC.2/Circ12/Rev.2)" by the International Maritime Organisation. (2018, April 9). https://wwwcdn.imo.org/localresources/en/OurWork/HumanElement/Documents/MSC-MEPC.2-Circ.12-Rev.2%20-%20Revised%20Guidelines%20For%20Formal%20Safety%20Assessment%20(Fsa)For%20Use%20In%20The%20Imo%20Rule-Making%20Proces...%20(Secretariat).pdf
Additional information on what the effects on the ship have been added to further illustrate the consequences of the accident.

5.2.4 Initial Risk Index

The values established for frequency and severity of the accident scenarios in chapter 5.2.2 and 5.2.3 are used in table 30 to get a risk index value.

Table 29*: Risk Index table*

FI	Frequency	Severity Index (SI)			
		1	2	3	4
		Minor	Significant	Severe	Catastrophic
7	Frequent	8	9	10	11
6		7	8	9	10
5	Reasonably probable	6	7	8	9
4		5	6	7	8
3	Remote	4	5	6	7
2		3	4	5	6
1	Extremely remote	2	3	4	5

Note: This table is a copy of the Risk Index table found on page 41 in the publication "Revised Guidelines for Formal Safety Assessment (FSA) for use in the IMO Rule-Making Process (MSC-MEPC.2/Circ12/Rev.2)" by the International Maritime Organisation. (2018, April 9). https://wwwcdn.imo.org/localresources/en/OurWork/HumanElement/Documents/MSC-MEPC.2-Circ.12-Rev.2%20-%20Revised%20Guidelines%20For%20Formal%20Safety%20Assessment%20(Fsa)For%20Use%20In%20The%20Imo%20Rule-Making%20Proces...%20(Secretariat).pdf

Using the frequency and severity from chapter 5.2.2 and 5.2.3 the result of the risk index of collision, grounding, and contact is 6, 6, and 3 respectively. While these risks are not egregiously high, there are still risk control options that could decrease the risk of the batteries catching fire due to deformation.

5.2.5 Risk Control Options

To mitigate the risks determined in chapter 5.2.4, either the frequency or the severity (or both) of the accident can be decreased to also decrease the risk of the accident. This report will focus on reducing the severity of the accident.

One way to decrease the risk of battery deformation in an accident is to place the batteries farther from the outer hull. As is presented in chapter 5.2.3 and table 17, many ships experiencing a collision accident receives damages deeper than 2 meters and placing them at least 3 meters in from the outer hull would lessen the likelihood of the batteries being deformed, as only one damage scenario resulted in damages deeper than 3 meters. In the case of grounding accidents, the majority of the transverse damages are not deeper than 2,5 meters into the ship, and only 10% of the vertical damages extend deeper than 2,63 meters (chapter 4.3.2).

It can therefore be determined that placing the batteries 3 meters in from the side and at least 2,5 meters above the bottom of the outer hull would reduce the risk of the batteries being deformed.

5.2.6 Accident Severity After Implementing the Risk Control Option.

Using the risk control option of placing the batteries 2,5 meters from the bottom of the outer hull and 3 meters in from the side of the outer hull, the severity of the accident can be reevaluated.

With the risk control option implemented, the risk of the batteries being deformed in a collision or grounding accident is lessened, the risk of fire is lowered as well, and the new severity index of those two accident scenarios is reduced to 2.

This battery placement would also lessen the risk of the batteries being deformed in a contact scenario, but as the severity index is already determined to be 1, it cannot be lowered more than that, and it therefore stays at the severity index of 1.

5.2.7 Risk Index After Risk Control Option

After implementation of the risk control option suggested in chapter 5.2.5 the risk index for collision and grounding accidents is determined to be 4, and the risk index for the contact scenario remains at 3, in accordance with table 30. The risk of fire has been reduced by decreasing the likelihood of the batteries being deformed as a consequence of external impact.

5.3 Discussion on Battery Placement

A discussion on the most suitable spaces and areas for battery placement is conducted in this section, and it will act as the last step of the formal safety assessment. The arguments are based on existing guidelines and recommendations from the maritime industry, as well as the statistical and simulation data in chapter 4.

5.3.1 Existing Recommendations on Battery Placement

It is stated in chapter 4.4.2 that each ship must follow the construction rules of the classification society that they employ, and one classification society has outright expressed that the batteries cannot be placed forward of the collision bulkhead. This can be compared to the requirements stated by the IMO in MARPOL, which is that no oil should be carried in the spaces forward of the collision bulkhead (chapter 2.5). The reason for this can be argued to be because the bow of the ship is almost always damaged when a ship strikes something, and that damage could lead to pollution if oil were to be carried in the fore peak. Damage of the batteries may not lead to pollution, but the desire to avoid a potential fire caused by deformed batteries would make it reasonable to not place batteries in that space either.

The guidelines on battery placement published by EMSA (chapter 2.1.2) states that batteries should be placed in areas of the ship that face a lower risk collision damage, but they do not specify which areas of a ship that is.

For electric vehicles, the common practice is to not place the battery pack within the collision deformation zones, which has proven to be an effective strategy, as several tests can be performed without the battery pack sustaining damage. The "safe zone" is between the wheel axles of the vehicle, and a bit in from the side of it (chapter 4.4.2).

5.3.2 Battery Placement Based on Statistics and Simulations.

In the longitudinal direction of the ship, collision damages are most likely to occur in the bow, as can be seen in table 15. Grounding damage is also likely to occur in the bow of the ship, especially around the forward perpendicular, as shown in table 20. In the same table it can also be seen that the aft half of the ship faces a higher risk of damage than the forward half.

In the transverse direction of the ship, collision damages occur along the sides of the hull, as the damage is delt by another ship. The statistics on the transverse location of grounding displayed in table 18 show that the sides of the hull are more likely to sustain damage, but that the area next to the keel has the highest likelihood. However, Liu et al (2021) found that the most common location for grounding damage was at the halfway point between the keel and the side of the ship (chapter 4.3.2). When those two findings are combined, essentially the entire hull bottom face the same likelihood of receiving damage.

In the vertical direction of the ship, collision damages mostly occur in the areas above the waterline, but a substantial amount of damage also occurs below the waterline (table 16). 78,5% of all collision scenarios result in at least some damage above the water line, while 43,5% of all scenarios result in at least some damage below the water line. Grounding damage is typically delt from the bottom of the hull.

This damage location data makes it possible to draw conclusions on which parts of a ship is less suitable to contain batteries.

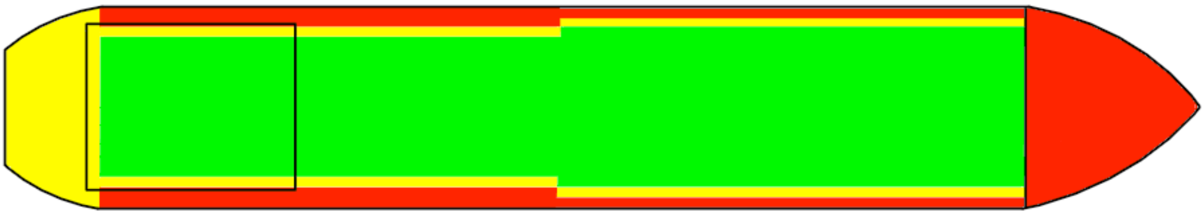
5.3.3 Summary of Battery Placement

To summarise the evaluation of locations from the previous sections in this chapter, it can be said that battery packs should not be placed forward of the collision bulkhead, and they should be kept at a distance aft of the forward perpendicular. Batteries should not be placed close to the bottom of the hull anywhere in the transverse direction and they should not be placed close to the side of the hull, especially in the aft half of the ship. Batteries should be placed at a minimum distance of 2,5 meters from the bottom of the outer hull and 3 meters from the side of the outer hull.

An illustration of the ship areas and how suitable they are to contain batteries is shown in figure 7 and figure 8. The green colour indicates areas with high suitability, yellow indicates intermediate suitability, and red indicates that it is not suitable to contain batteries. The red and yellow areas take a form that can be likened with the collision zones in a vehicle, that is, that the very from and the very back of the vessel are deformation zones and are meant to protect the passengers, and that there is also a bit of a safety margin on the sides as well. The "safe zone" for batteries can be considered to be as close to the very centre of the ship as possible, where the risk of any foreign object reaching them is the lowest.

Figure 7 shows that batteries should be kept away from the bow area forward of the collision bulkhead, and placement aft of the aft bulkhead should be avoided if possible. Batteries should not be placed close to the outer hull, the red areas next to the hull symbolises the 3-meter distance between battery packs and the outer hull that is described in chapter 5.2.5. The yellow area next to the red ones that run along the side of the hull indicates an extra safety margin, as there were some collision statistics that showed that there have been damages that penetrated deeper than the recommended 3 meters, but it was not common. The yellow zone can therefore be seen as an area that should not contain batteries if it is possible to avoid it. The breadth of the yellow safety margin has not been determined in this report, as there are some grounding accidents that result in damages a lot deeper than 3 meters (table 19b). This makes it difficult to decide a universal measure for the safety margin, but it can still be said that by adding a safety margin of 1 meter, making the total distance from the side of the outer hull 4 meters, more than 80% of all accidents recorded result in damage depths equal to or less than that distance. Since there is a higher statistical likelihood of a ship receiving damage in the aft half of the vessel in a grounding accident, the red and yellow areas next to the side of the outer hull have been drawn slightly thicker than those in the forward half to illustrate this. This is also true for the collision accidents if the damages in the bow area are excluded, as can be seen in table 15.

Figure 6. *Battery placement seen from above.*



Note: Recommended areas for battery placement, seen from above. Red indicates areas that should not contain batteries, yellow indicates areas that could contain batteries if necessary, and green indicates areas that are best suited to contain batteries.

Figure 8 shows that batteries should not be placed in the bow area and forward of the collision bulkhead, for the same reasons as stated in the previous paragraph. It also shows that batteries should not be placed close to the bottom of the outer hull, as the risk for grounding damage is the highest there. The red area in the bottom symbolises the recommended distance of 2,5 meters that is described in chapter 5.2.5. The yellow area next to it is a safety margin of undetermined width, but adding another half meter of distance between the bottom of the outer hull and the battery location would satisfy the vertical grounding damage extent presented in chapter 4.3.2. Since the likelihood of sustaining collision damage is higher above the waterline as presented in table 16, the area below the waterline is green and the area above the waterline is yellow to illustrate this. Placing batteries above the waterline could still be done however, provided that the distance from the outer hull follows the recommendations made for figure 7 above.

Figure 7. *Battery placement seen from the side.*

Note: Recommended areas for battery placement, seen from the side. Red indicates areas that should not contain batteries, yellow indicates areas that could contain batteries if necessary, and green indicates areas that are best suited to contain batteries.

Following these recommendations would mean that the batteries cannot be placed in the double hull spaces, at least not a double hull space with the distances determined by MARPOL in chapter 2.5 and table 1. Doing so would increase the risk of a fire that is difficult to extinguish, which could cause significant damage to the ship itself, as well as compromising the safety of those onboard. As maritime accidents mainly occur close to shore (table 10) and the batteries are charged during the port stay, this could infer that a potential accident resulting in hull damage is likely to happen when the batteries are fully or almost fully charged, which means that a resulting fire would burn in a very aggressive manner, as described in chapter 2.1.2. A thermal runaway caused by mechanical abuse and short circuiting does not only cause a "normal" fire, as it can also lead to emissions of toxic and flammable gases and even explosions, and the consequences of such events cannot be underestimated.

5.4 Discussion on the Results

The results from the information search and the following risk assessment shows that there should be a safety distance between the location of the battery packs and the outer hull in the longitudinal, transverse, and vertical direction. The safety distance varies somewhat depending on the part of the hull and the direction of the deformation, but the transverse distances from the side of the hull should be at least 3 meters and the vertical distance from the bottom of the hull should be at least 2,5 meters, and there should not be any batteries forward of the collision bulkhead. These recommendations can make it seem like a lot of potential battery space is wasted, but the recommendations do not mean that those areas cannot be used for some other purpose, such as ballast tanks which are already common in such spaces. Additionally, a fully electric battery ship has no need of the enormous engines or fuel tanks that are usually installed on diesel ships, and not having them clears up room for potential battery spaces that do not impact the cargo spaces in a negative way.

The information found on accident numbers and statistics give a clear indication that some parts of a ship are more likely to sustain damage in certain accidents. There are also clear indications that some accident types are more prevalent than others, and that the most common accident type can vary between different sea areas. This was expected, as different ports, shipping lanes, and sea areas provide varying forms of obstacles and hazards that ships need to face. However, when the statistics for the various accident types were calculated in calculation 2, it was surprising to see that all three accident types occurred with the same magnitude of 10^{-4}. The numbers of contact and grounding scenarios were expected to be higher than they were, especially when compared to collision scenarios. A possible reason for this result is discussed further in chapter 5.5. Having more sources on the subject might have shifted the outcome of the probability calculations, but finding quality sources of that kind were not as easy as expected. Most of the sources that were used to gather the statistics needed were published by government agencies and similar organisations who openly admits that there most probably are a high number of accidents that go unreported, and that it skews the statistics in a more favourable way. Sormunen et al (2016) also admitted that this was a problem for them, and they estimated that the true number of accidents could be at least twice as high as the one recorded. This fact can make the numbers and calculations made in the risk assessment too optimistic when it comes to the frequency of the accidents and is something that could be taken into consideration when evaluating the frequency of an event.

Statistics on the resulting damage in an accident were also challenging to find, and simulations on accident damage seemed to be more prevalent. There was one source that provided most of the information on the damage location and extent in collision and grounding accidents, namely the article by Pilatis et al (2024). This article was by far the most detailed source found with such statistics and was invaluable to this report. The other two sources used simulations or simulations in combination with statistics to conduct their study. Another challenge that was encountered, which was also unexpected, was that no statistics on the damage extent caused by contact with floating objects or manmade structures could be found. This is theorised to be because such occurrences result in minimal damage to the ship, or that they are not even noticed when they happen. Larger floating objects that could potentially deal some substantial damage to a ship, such as containers, could possibly be easier to discover and avoid, and therefore not cause damage to the ship. Still, for being such a common accident type, it was strange that no real statistics on the resulting damages could be found.

Finding statistics on battery cell deformation was considerably easier than finding the other statistics needed for the report. The statistics found matched each other quite well and showed that battery cells do not tolerate a deformation more significant than a few millimetres before an internal short circuit occurs. Something that would have been even more relevant however would be if there had been any statistics found not only on deformation at cell level, but also at module and pack level as well. This is because the battery cells are normally arranged in modules and packs as stated in chapter 2.1.1, and the added material and structure around the battery cells could give them an increased resistance to deformation. On the other hand, the values that were found and used in this report can act as a worst-case scenario regarding the allowable battery deformation.

5.5 Discussion on the Method

The method used for this report was a systematic literary study in combination with a risk assessment. The two books used as guides for this report have enabled this report to follow a scientific structure and to present the results from the information search in a transparent, meticulous, and organised way. Denscombe (2014) writes that a systematic review is well suited for a report that makes decisions based on high quality evidence, and that it is suitable for subjects that already has research findings based on quantitative data. Using this method was appropriate as there is previous research done on the subjects relevant to this study, and the narrative is based on all the sources of information found that fit the standards established to ensure their quality and relevancy, and because the results and conclusions are made objectively based on the information found.

Having few sources on each subject relevant to the study can be a hindrance to making generalisations based on statistics and averages, and a lot of effort was therefore made to find several different sources on the same subject. This was also done in order to decrease the risk of finding a biased source, as cross checking the information between similar sources makes potential bias easier to discover. If the information from them proved to be consistent, then they could be considered as being reliable and accurate. This is even more true for sources that had been independently peer reviewed by various academic journals, which is why one of the inclusion criteria established for the information search was that the academic articles had to have been peer reviewed, which ensures their quality.

Another method that could have been used for chapters 4.2 and 4.3 is a quantitative study, where existing maritime accident reports could have been investigated and the information collected into statistics, but this was not feasible for this report due to time constraints. Because of this, the method chosen was a systematic literature review, which made it possible to utilize sources with information that had already been gathered and compiled into statistics. This also made it possible to assess statistics compiled by different authors and for different areas of the world, to learn about the discoveries they made, and to compare those results to each other.

Using statistics as a basis for this report in some cases proved to be more difficult than expected, mostly because it was challenging to find information on the number of ship movements or port calls within a certain area to which the reported accidents and incidents in the same area could be compared to form a basis for the frequency index. Comparing very different maritime areas gives an average value of the number of accidents from all the sources, but doing so might give a statistical value that is not entirely accurate to any specific area. For example, collision accidents may not be common in port areas that does not experience a lot of traffic, but grounding accidents might be more common if the port area has many underwater obstacles. This can be the reason as to why some of the accident statistics found appeared to be too low, yet they could be perfectly accurate for the specific area investigated. If a ship owner knows that a ship is intended for use in a particular area, it could be more appropriate to conduct a risk assessment for those areas specifically. This should also be done when it comes to the severity of the damage delt to the ship in question, as the construction could vary with different ship types and the materials used, and thereby the outcome of the accident may not be the same for every ship.

The method used for the risk assessment is one of the most common methods within the maritime industry since it is frequently used by the IMO themselves. Using matrixes or tables to figure out the frequency and severity of a particular accident scenario and to then combine them to get an index number on the risk is a simple and accessible way to conduct such an investigation. This method was chosen because it is so prevalent within the industry and the structure is easy to follow.

By combining the two methods the goal of investigating risks based on statistical numbers could be achieved. The validity and reliability of the statistics found were ensured as much as possible by finding a variety of sources and evaluating their quality, but since there is a suspected underreporting of accidents, the results of the statistics cannot be guaranteed to be truly accurate to the real number of accidents and their consequences. The same fact can be said of how many port calls are made in a certain area every year and how significant the damages are, as that might not be recorded in detail. Still, the statistics provide a generalised overview of ship accidents that occur and the results thereof, and they made this report possible.

6. CONCLUSION

The purpose of this study was to investigate where ships are damaged the most when it comes to frequency and extent of damage, how well-suited double hull spaces are for containment of battery packs, and if placing batteries in those spaces can be justified by the risk. The conclusions that can be made based on the results found and the discussion conducted in previous chapters of this systematic literature review are as follows:

The parts of a ship that is most likely to sustain damage in a collision and grounding event is the bow area, followed by the by the bottom and sides of the hull the aft half of the ship. Most vertical damage is delt above the waterline, but a substantial amount is delt under the waterline as well. The damages generally extend at least 2,5 meters from the outer hull towards the centre of the ship, and often the damage is much deeper than that.

This means that batteries should be placed as close to the centre of the ship as possible in order to avoid external damages in any such accident event, and thereby ensuring the safety of the batteries and preventing battery fires as a consequence of a thermal runaway caused by mechanical abuse. The battery placement of course needs to be evaluated against the placement of the cargo hold, and some sort of compromise must be reached that satisfies the needs of both spaces.

Placing batteries close to the outer hull or within double hull spaces cannot be recommended, at least not if the double hull is constructed according to the requirements in annex I of the MARPOL convention (International Maritime Organisation, n.d.B). As battery cells can tolerate very little deformation before having an internal short circuit, the consequences of which can be catastrophic, it is not advisable to place them in areas where they would be in harms way during an accident. Because of the potential consequences of such an accident and fire, for example extensive ship damage, loss of cargo, loss of life, and loss of ship, the goal of increasing the range of operation by fitting more batteries in the space close to the hull cannot be justified by the risk.

7. RECOMMENDATIONS FOR FURTHER RESEARCH

There are several topics and aspects of ship construction and stability, battery variations, and economical matters that have not been considered in this report, as can be seen in the Delimitations part in the introduction. Those delimitations are examples of subjects that could be investigated further in future work, and they are as follows:

- Further investigation could be made into how placement of batteries within different parts of the hull spaces could affect the stability of the vessel. Batteries are in general heavy and dense, and the distribution of added weight could impact the loading conditions of the ship. Placing battery packs in some parts of the hull spaces could therefore affect the stability characteristics of the ship, which is something that must be considered from a stability safety perspective.
- As new battery types develop, there may very well be other battery types that are suited even better for use in a maritime environment, both from a safety and efficiency perspective.
- For battery safety measures it would be interesting to see how adding active fire protection and prevention systems would affect the risk involved with batteries and if they could be placed in more vulnerable positions.
- Batteries are still a quite expensive, and placing more of them on a ship to increase the operational range might not be economically feasible. Adding batteries could not only affect the stability of a ship, but it would also increase the weight of the ship, and doing so might also decrease the efficiency of the vessel. Therefore, the economic standpoint on adding more batteries to a ship could be further investigated.
- Are battery ships the best solution to achieve a shipping industry with lower global greenhouse emissions? How sustainable is it really to equip a ship with batteries, compared to developing alternative fossil free fuels, will the initial environmental impact be offset by lower emissions during the lifetime of the vessel?

REFERENCES

Antão, P., Sun, S., Teixeira, A.P., & Guedes Soares, C. (2023). Quantitative Assessment of Ship Collision Risk Influencing Factors from Worldwide Accident and Fleet Data. *Reliability Engineering & System Safety*. Volume 234. https://doi.org/10.1016/j.ress.2023.109166

Anwar, S., Zia, M.Y.I., Rashid, M., de Rubens, G.Z., & Enevoldsen, P. (2020). Towards Ferry Electrification in the Maritime Sector. *Energies* 13(24). https://doi.org/10.3390/en13246506

Australian Academy of Science. (2016, February 25). *How A Battery Works.* https://www.science.org.au/curious/technology-future/batteries

Babb, C.E. (2015). The Curious History of Electric Ship Propulsion. *Future Force Magazine*, 2(3), 6-9, https://www.nre.navy.mil/media/document/future-force-6-summer-2015pdf

Bisschop, R., Willstrand, O., Amon, F., & Rosengren, M. (2019). *Fire Safety of Lithium-Ion Batteries in Road Vehicles.* Research Institute of Sweden. https://ri.diva-portal.org/smash/record.jsf?pid=diva2%3A1317419&dswid=2250

Bisschop, R., Willstrand, O., & Rosengren, M. (2020). Handling Lithium-Ion batteries in Electric Vehicles: Preventing and Recovering from Hazardous Events. *Fire Technology*, Volume 56, 2671-2694. https://doi.org/10.1007/s10694-020-01038-1

Burton, N. (2013) *A History of Electric Cars* (1st ed). Crowood. ISBN 978 1 84797 571 3

Chombo, P.V., Laoonual, Y., & Wongwises, S. (2021). Lessons from the Electrical Vehicle Crashworthiness Leading to Battery Fire. *Energies*, 14(16), 4802. https://doi.org/10.3390/en14164802

Denscombe, M. (2014). *The Good Research Guide: for small scale research.* (5th ed). Open University Press. ISBN 978 033 526 4711

Endrina, N., Rasero, J.C., & Konovessis, D. (2018). Risk Analysis for RoPax Vessels: A Case of Study for the Strait of Gibraltar. *Ocean Engineering*, Volume 151. 141-151. https://doi.org/10.1016/j.oceaneng.2018.01.038

Enge, P., Enge, N., & Zoepf, S. (2020). *Electric Vehicle Engineering* (1st ed). McGraw-Hill Education.

Engineering and Technology History Wiki. (2014, November 21). *Marine Turboelectric Drive.* https://ethw.org/Marine_turboelectric_drive

European Alternative Fuels Observatory. (n.d.). *Ships with Batteries.* Retrieved April 15, 2024 from https://alternative-fuels-observatory.ec.europa.eu/transport-mode/maritime-sea/vessels

European Environment Agency. (2024, January 10). *Electric Vehicles.* https://www.eea.europa.eu/en/topics/in-depth/electric-vehicles

European Maritime Safety Agency. (2023, October 27). *Annual Overview of Marine Casualties and Incidents 2023.* https://www.emsa.europa.eu/publications/reports/item/5052-annual-overview-of-marine-casualties-and-incidents.html

European Maritime Safety Agency. (2023, November 14). *Guidance on the Safety of BESS On Board Ships.* https://www.emsa.europa.eu/electrification/bess.html

European Maritime Safety Agency. (2017). *Marine Casualties and Incidents: Summary Overview 2011-2015.* https://www.emsa.europa.eu/component/flexicontent/download/4685/3011/23.html

European Maritime Safety Agency. (2020, May 7). *Study on Electrical Energy Storage for Ships*. https://www.emsa.europa.eu/publications/item/3895-study-on-electrical-energy-storage-for-ships.html

Eurostat. (2023, December 13). *Maritime Freight and Vessel Statistics.* https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Maritime_ports_freight_and_passenger_statistics&oldid=218671

International Association of Classification Societies. (2024, January 1). *Common Structural Rules for Bulk Carriers and Oil Tankers*. https://iacs.s3.af-south-1.amazonaws.com/wp-content/uploads/2024/03/18145737/CSR-H-01-JAN-2024.pdf

International Maritime Organisation (n.d.A). *Formal Safety Assessment.* https://www.imo.org/en/OurWork/Safety/Pages/FormalSafetyAssessment.aspx

International Maritime Organisation. (n.d.B). *International Convention for the Prevention of Pollution from Ships (MARPOL).* Retrieved March 15, 2024, from https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx

International Maritime Organisation (n.d.C). *International Convention for the Safety of Life at Sea (SOLAS).* https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx

International Maritime Organisation. (n.d.D). *International Convention on Load Lines (ILLC). Annex I.* http://dmr.regs4ships.com/

International Maritime Organisation (n.d.E) MARPOL. *Annex I.* http://dmr.regs4ships.com/

International Maritime Organisation (2018, April 9). *Revised Guidelines for Formal Safety Assessment (FSA) for use in the IMO Rule-Making Process (MSC- MEPC.2/Circ12/Rev.2).* https://wwwcdn.imo.org/localresources/en/OurWork/HumanElement/Documents/MSC-MEPC.2-Circ.12-Rev.2%20-%20Revised%20Guidelines%20For%20Formal%20Safety%20Assessment%20(Fsa)For%20Use%20In%20The%20Imo%20Rule-Making%20Proces...%20(Secretariat).pdf

International Maritime Organisation (n.d.F) SOLAS. *Chapter II-1.* http://dmr.regs4ships.com/

Jesson, J. K., Matheson, L., & Lacey, F.M. (2011). *Doing Your Literature Review – Traditional and Systematic Techniques.* (1st ed). Sage.

Kisters, T., Sahraei, E., & Wierzbicki, T. (2017). Dynamic Impact Tests on Lithium-ion Cells. *International Journal of Impact Engineering*, Volume 108, 205-216. https://doi.org/10.1016/j.ijimpeng.2017.04.025

Keane, A. (2023) Buckle Up: Electrification of Transport is Happening [In My View]. *IEEE Power and Energy Magazine*, 21(6), 114-116. https://doi.org/10.1109/MPE.2023.3308249

Liu, B. (2017). Analytical Method to Assess Double-Hull Ship structures Subjected to Bulbous Bow Collision. *Ocean Engineering*, volume 142, 27-38. https://doi.org/10.1016/j.oceaneng.2017.06.062

Liu, B., Villavicencio, R., Terndrup Pedersen, P., & Guedes Soares, C. (2021). Analysis of Structural Crashworthiness of Double-hull Ships in Collision and Grounding. *Marine Structures.* Volume 76. https://doi.org/10.1016/j.marstruc.2020.102898

Liu, X., Zhao, F., Geng, J., Hao, H., & Liu, Z. (2023) Comprehensive Assessment for Different Ranges of Battery Electric Vehicles: Is it Necessary to develop an Ultra-Long Range Battery Electric Vehicle? *iScience*, 26(6). https://doi.org/10.1016/j.isci.2023.106654

Matulka, R. (2014, September 15). *The History of the Electric Car.* U.S. Department of Energy. https://www.energy.gov/articles/history-electric-car

Mikkola, N., Randall, L., & Hagberg, A. (2016, September 25). *Ampere, the World's First Electric Ferry*. Green Growth in Nordic Regions – 50 Ways to Make it Happen. 90-91. https://nordregio.org/publications/green-growth-in-nordic-regions-50-ways-to-make-it-happen/

Mjøs, N., Eriksen, S., Kristoffersen, A., Haugom, G.P., Huser, A., Gully, B., Hill, D., Stoiber, R., Valøen, L.O., & Mollestad, E. (2016, December 19). *DNV GL Handbook for Maritime and Offshore Battery Systems.* Det Norske Veritas. https://www.dnv.com/maritime/publications/maritime-and-offshore-battery-systems-download/

Moon, J., Chang, H., Lee, J., & Kim, C.W. (2022). Prediction of Internal Circuit and Mechanical-Electrical-Thermal Response of Lithium-Ion Battery Cell with Mechanical-Thermal Coupled Analysis. *Energies*, 15(3). https://doi.org/10.3390/en15030929

Moseman, A., & Paltsev, S. (2022, October 13) *Are Electric Vehicles Definitely Better for the Climate Than Gas-Powered Cars?* MIT Climate Portal. https://climate.mit.edu/ask-mit/are-electric-vehicles-definitely-better-climate-gas-powered-cars

Mylenbusch, I.S., Claffey, K., & Chu, B.N. (2023). Hazards of Lithium-Ion Battery Energy Storage Systems (BESS), Mitigation Strategies, Minimum Requirements, and Best Practices. *Process Safety Progress,* 42(4), 664-673. https://doi.org/10.1002/prs.12491

Newaz, G., Mundhe, S., Arava, L., Zhu, M., Faruque, O., & Barbat, S. (2020). Direct Assessment of Separator Strain in Li-Ion Batteries at the Onset of Mechanically Induced Short Circuit. *Energies,* 13(3), 669. https://doi.org/10.3390/en13030669

Paul. D. (2020) A History of Electric Ship Propulsion Systems [History]. *IEEE Industry Applications Magazine,* 26(6), 9-19. https://doi.org/10.1109/MIAS.2020.3014837

Pilatis, A.N., Pagonis, D.N., Serris, M., Peppa, S., & Kaltsas, G. (2024). A Statistical Analysis of Ship Accidents (1990-2020) Focusing on Collision, Grounding, Hull Failure, and Resulting Hull Damage. *Journal of Marine Science and Engineering,* 12(1), 122. https://doi.org/10.3390/jmse12010122

Qin, D., Wang, P., Wang, T., & Chen, J. (2023). Modelling and Dynamic Impact Analysis of Lithium-ion Battery. *Sustainability*, 15(10), 8414. https://doi.org/10.3390/su15108414

Sormunen, O.V.E., Hänninen, M., & Kujala, P. (2016). Marine Traffic, Accidents, and Underreporting in the Baltic Sea. *Scientific Journals of the Maritime University of Szczecin*, 118(46), 163-177. https://repository.am.szczecin.pl/handle/123456789/1224

Spielbauer, M., Berg, P., Ringat, M., Bohlen, O., & Jossen, A. (2019). Experimental Study of the Impedance Behaviour of 18650 Lithium-ion Battery Cells under Deforming Mechanical Abuse. *Journal of Energy Storage*, Volume 26. https://doi.org/10.1016/j.est.2019.101039

Stena Line. (n.d.). *Stena Elektra – from Vision to Vessel.* Retrieved April 15, 2024, from https://stenaline.com/stena-elektra-from-vision-to-vessel/

Swedish Transport Agency. (2023, May 29). *Säkerhetsöversikt sjöfart 2022.* https://www.transportstyrelsen.se/sv/publikationer-och-rapporter/rapporter/sjofart/sakerhetsoversikt-sjofart-2022/

Trombetta, G.L., Leonardi, S.G., Aloisio, D., Andaloro, L., & Sergi, F. (2024). Lithium-Ion Batteries on Board: A Review on Their Integration for Enabling the Energy Transition in Shipping Industry. *Energies,* 17(5), 37. https://doi.org/10.3390/en17051019

University of Chicago Library. (2023, September 7). *The CRAAP Test.* https://guides.lib.uchicago.edu/c.php?g=1241077&p=9082343

Voyiadjis, G.Z., Akbari, E., Łuczak, B., & Sumelka, W. (2023). Towards Determining an Engineering Stress-Strain Curve and Damage of the Cylindrical Lithium-Ion Battery

Using the Cylindrical Indentation Test. *Batteries*, 9(4), 233. https://doi.org/10.3390/batteries9040233

Wang, G., Wu, J., Zheng, Z., Niu, L., Pan, L., & Wang, B. (2022). Effect of Deformation on Safety and Capacity of Lithium-Ion Batteries. *Batteries*, 8(11), 235. https://doi.org/10.3390/batteries8110235

Willstrand, O., Bisschop, R., Blomqvist, P., Temple, A., & Anderson, J. (2020). *Toxic Gases from Fire in Electric Vehicles.* Research Institute of Sweden. https://ri.diva- portal.org/smash/get/diva2:1522149/FULLTEXT01.pdf

Wärtsilä. (n.d). *Full Electric Vessels.* Retrieved April 17, 2024, from https://www.wartsila.com/marine/products/ship-electrification-solutions/full-electric-vessels

Zhang, L., Wang, H., Meng, Q., & Xie, H. (2019). Ship Accident Consequences and Contributing Factors Analyses using Ship Accident Investigation Reports. *Journal of Risk and Reliability*, 233(1), 35-47. https://doi.dox.org/10.1177/1748006X18768917

APPENDIX 1

A detailed table with information on the sources found in chapter 4.

Authors	Type of source	Year of publishing	Search engine /database	Subject
Pilatis, A.N., Pagonis, D.N., Serris, M., Peppa, S., & Kaltsas, G.	Article	2024	Web of Science	Damage extent on hull (statistics)
Swedish Transport Agency	Publication	2023	Google	Maritime accident statistics (Sweden)
Antão, P., Sun, S., Teixeira, A.P., & Guedes Soares, C.	Article	2023	Web of Science	Maritime accident statistics (global)
Liu, B., Villavicencio, R., Terndrup Pedersen, P., & Guedes Soares, C.	Article	2021	Web of Science	Damage extent on hull (statistics, simulations)
Endrina, N., Rasero, J.C., & Konovessis, D.	Article	2018	Web of Science	Maritime accident statistics (Strait of Gibraltar)
Chombo, P.V., Laoonual, Y., & Wongwises, S.	Article	2021	Chalmers library	Electric vehicle safety (crash)
Moon, J., Chang, H., Lee, J., & Kim, C.W.	Article	2022	Web of Science	Deformation of battery cell (pouch)
Wang, G., Wu, J., Zheng, Z., Niu, L., Pan, L., & Wang, B.	Article	2022	Web of Science	Deformation of battery cell (cylindrical)
Voyiadjis, G.Z., Akbari, E., Łuczak, B., & Sumelka, W.	Article	2023	Chalmers library	Deformation of battery cell (cylindrical)
Qin, D., Wang, P., Wang, T., & Chen, J.	Article	2023	Web of Science	Deformation of battery cell (prismatic)
Trombetta, G.L., Leonardi, S.G., Aloisio, D., Andaloro, L., & Sergi, F.	Article	2024	Chalmers library	Integration of batteries on a ship
Mjøs, N., Eriksen, S., Kristoffersen, A., Haugom, G.P., Huser, A., Gully, B., Hill, D., Stoiber, R., Valøen, L.O., & Mollestad, E.	Publication	2016	Google	Battery handbook for maritime use
Liu, B.	Article	2017	Web of Science	Damage extent on hull (Simulation)
European Maritime Safety Agency	Publication	2023 (October 27)	Google	Maritime accident statistics (Europe)
Eurostat	Publication	2023	Google	Maritime accident statistics (Europe)

Sormunen, O.V.E., Hänninen, M., & Kujala, P.	Article	2016	Chalmers library	Maritime accident statistics (Baltic Sea)
Spielbauer, M., Berg, P., Ringat, M., Bohlen, O., & Jossen, A.	Article	2019	Web of Science	Deformation of battery cell (cylindrical)
Newaz, G., Mundhe, S., Arava, L., Zhu, M., Faruque, O., & Barbat, S.	Article	2020	Web of science	Deformation of battery cell (pouch)
Kisters, T., Sahraei, E., & Wierzbicki, T.	Article	2017	Chalmers library	Deformation of battery cell (pouch, prismatic)
Bisschop, R., Willstrand, O., Amon, F., & Rosengren, M.	Publication	2019	Google	Electric vehicle safety (fire)

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