SAPIENZA
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The Use of Autonomous Vessels and Applicability to Emergency Humanitarian Response

Faculty of Civil and Industrial Engineering
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Abstract

Technological developments are making the transportation sector more multifaceted and complex, posing both challenges and opportunities. These new technologies allow for an improvement in safety, emissions, expenditures and productivity, but at what cost? In recent years, autonomous technology has taken the forefront in not only the shipping sector, but the transportation domain as a whole. The concept of autonomous vessels has become the latest high-tech advancement discussed by the United Nations (UN) International Maritime Organization (IMO) which currently has ongoing scoping exercises to evaluate the safety, environmental and security aspects of operating Maritime Autonomous Surface Ships (MASS).

IMO is a specialized agency within the UN responsible for shipping regulations, and with the projected growth in transport volumes, a need to address new technologies involving automation is essential. Autonomous vessels must have the capability to maneuver safely and cost-effectively in the presence of hazards and have the power to sense the surrounding environment instantaneously. This thesis will further analyze the costs and environmental impacts associated with running an autonomous vessel and compares the results with a traditional vessel of the same magnitude. Furthermore, this investigation will be conducted in a general context and in the framework of a humanitarian emergency, involving projected forecasts of growth in the maritime sector.

The case study chosen for this report is modeled after the World Food Programme (WFP) as it is the only branch of the UN with its own shipping unit handling international cargo movements by sea. A bulk carrier vessel transporting humanitarian commodities such as bulk sorghum, wheat and bagged flour is chosen for this analysis due to its versatility and since WFP ships these items to fight worldwide hunger during emergencies.

The use of these autonomous technologies, specifically MASS, is projected to be a progressive change over time due to its need for proper safety and legal regulations, but the results of the study confirm that there are potential economic and environmental benefits associated with the implementation of autonomous vessels and their use of new fuel technologies and ship designs. Currently, there are no published studies involving an autonomous vessel and its relation to humanitarian emergency response.

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List of Abbreviations

AAWA	Advanced Autonomous Waterborne Applications
AIS	Automatic Identification System
AL	Autonomy Levels
CO2	Carbon Dioxide
COLREGs	International Regulations for Preventing Collisions at Sea
DWT	Deadweight tonnage
EEDI	Energy Efficiency Design Index
GHG	Greenhouse Gas Emissions
GPS	Global Positioning System
HFO	Heavy Fuel Oil
ICCT	International Council on Clean Transportation
ICS	International Chamber of Shipping
IEA	International Energy Agency
IMO	International Maritime Organization
IOM	International Organization for Migration
ISM	International Safety Management Code
ISPS	International Ship and Port Facility Security
ITF	International Transport Workers' Federation
ITF	International Transport Forum
IPCC	Intergovernmental Panel on Climate Change
LR	Lloyd's Register Group Limited
LSCI	Liner Shipping Connectivity Index
MARPOL	Marine Pollution
MARSRWG	Maritime Autonomous Systems Regulatory Working Group
MASS	Maritime Autonomous Surface Ships
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MSC	Maritime Safety Committee
MT	Metric Ton
MUNIN	Maritime Unmanned Navigation through Intelligence in Networks
OECD	Organization for Economic Co-operation and Development
SAE	Society of Automotive Engineers
SAR	Search and Rescue
SCC	Shore-based Control Center
SDG	Sustainable Development Goals
SOLAS	Safety of Life at Sea
STCW	Standards of Training, Certification and Watchkeeping for Seafarers
TCC	Total Crew Cost

TEU	Twenty-foot Equivalent Units
UAV	Unmanned Aerial Vehicle
UNCTAD	United Nations Conference on Trade and Development
USNA	United States Naval Academy
WMU	World Maritime University

1 Introduction

1.1 The Maritime Sector and the Future of Automation

Shipping is a main pillar in worldwide trade as it currently handles approximately 80 percent of the global trade volume and approximately 90 percent of developing countries' volume of international trade (UNCTAD, 2015). Maritime transportation demand is heavily influenced by the world economy and with a forecasted increase in overall transportation demand, there will be a large surge in the corresponding transport volume. World seaborne trade grew by 2.1 percent in 2015 (UNCTAD, 2016), and a World Maritime University (WMU) report projects the following trends in the world seaborne trade as shown in Table 1.

Table 1: Projected Growth in World Seaborne Trade (adapted from WMU, 2019)

By Year	World Seaborne Trade (billion ton-miles)
2020	60000
2030	74000
2040	84500

The introduction of new autonomous technologies depends heavily on the current regulations in place and how safely these goals can be accomplished. With recent prioritization of renewable energy in the maritime sector, this is even more of a reason to implement such technology as it will allow vessels to operate more efficiently. The adoption of autonomous ships under human supervision is expected to reach between 11 and 17 percent by 2040, as shown in Figure 1. The hope is that these ships will maneuver in national and regional jurisdictions and specialized trades. (WMU, 2019).

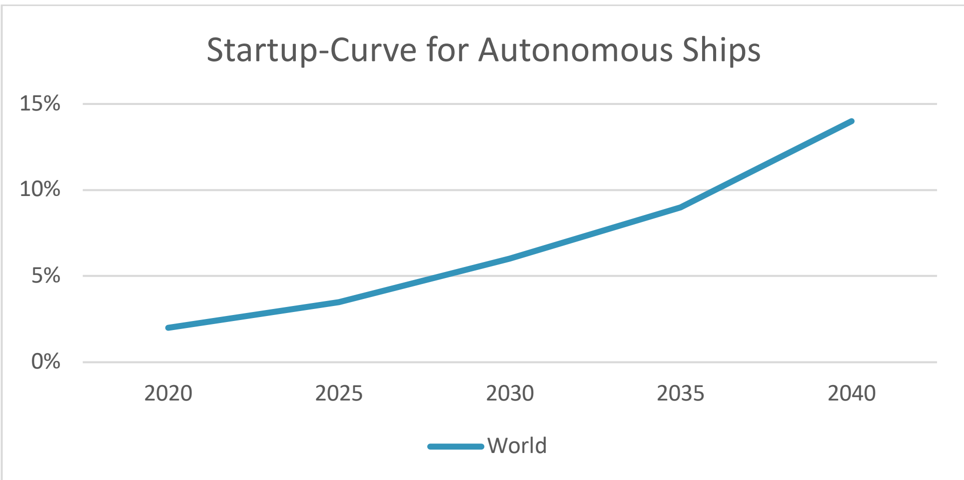

Figure 1: Startup-Curve for Autonomous Ships with Human Supervisions (adapted from WMU, 2019)

1.2 Purpose

The objective of this thesis is to compare a traditional bulk vessel to an autonomous bulk vessel in terms of the environmental impacts and operating, voyage and capital costs. The research question below will be addressed:

How are autonomous vessels a beneficial addition to the shipping industry, in terms of cost savings and emission reductions?

In addition, a case study evaluation of a geared autonomous bulk vessel with a specific design route will be modeled in a humanitarian context after WFP operations. An additional research question will be dealt with:

Are the use of autonomous vessels feasible in an emergency humanitarian context and what are the benefits associated with their use?

1.3 Limitations

This thesis will focus only on the aspects of ocean transportation and not consider links with other logistics nodes. Additionally, there will be a discussion regarding the technical, economic and safety issues of using an autonomous vessel, but only the cost and environmental data is presented in detail. The legal framework is not discussed in this report.

A large limitation of this thesis is related to data availability concerning autonomous shipping. The results are based on existing data from traditional vessels in terms of costs and CO_2 emissions and then related to potential cases involving autonomous vessels and their potential estimated improvement rates. There are ambiguities associated with the cost data and many assumptions rely on the existing information for traditional bulk vessels.

2 Background

2.1 United Nations Sustainable Development Goals

A motivation for exploring this subject concerned the UN's 2030 Agenda for Sustainable Development, where the UN's 193 Member States adopted 17 Sustainable Development Goals (SDGs) in September 2015 involving the "people, planet and prosperity" that can be applied to all countries. IMO has specifically established innovative and targeted maritime policies to respond to needs and promote sustainable maritime transportation, which will improve the safety and security of international shipping as a whole.

Figure 2: SDG Logo and Colour Wheel (United Nations)

Goal 14 addresses Life Below Water, which involves the environmental protection of the oceans, seas and marines resources for sustainable development. Completely addressing marine pollution, climate change and the conservation and sustainable use of oceans and resources.

Figure 3: SDG Goal #14 - Life Below Water (United Nations)

Goal 2 tackles Zero Hunger, a SDG promoted by both IMO and WFP, with a goal to end hunger and achieve food security. World trade depends on maritime transportation to carry goods in the most fuel and cost effective way and IMO provides that global, uniform system for industry regulation, assisting developing countries in building and ensuring the safe, secure, environmentally-friendly flow of maritime commerce. In addition, IMO provides the regulatory framework to improve maritime security for ships and port facilities to endorse methods "to combat piracy and armed robbery" (IMO).

Figure 4: SDG Goal #2 - Zero Hunger (United Nations)

An example that can be applied in relation to the case study is the Djibouti Code of Conduct. This Code of Conduct concerned the repression of piracy and armed robbery against ships in the Western Indian Ocean and the Gulf of Aden and provided the framework for capacity building in the Western Indian Ocean and the Gulf of Aden to offset the piracy threat.

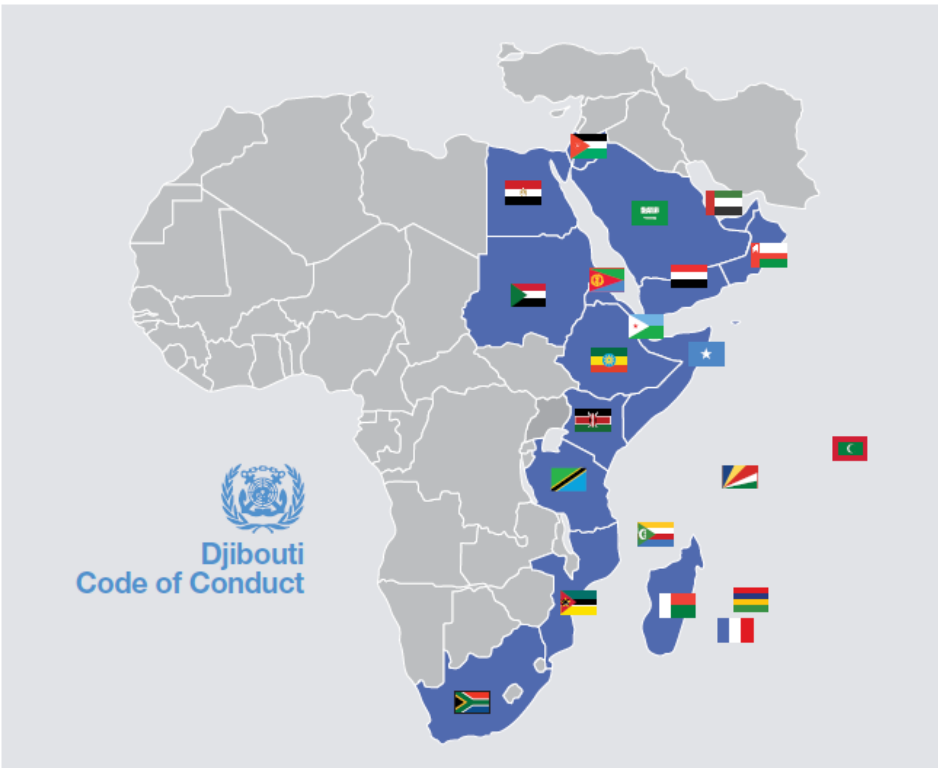

Figure 5: Djibouti Code of Conduct Map (IMO, 2015)

Another relevant SDG goal is number 13 addressing climate change and its impacts. IMO seeks to combat climate change, including air pollution, energy efficiency and greenhouse gas (GHG) emissions from shipping and has put in place many global regulations and standards to ensure the energy efficiency continues to improve in the maritime sector.

Figure 6: SDG Goal #13 - Climate Action (United Nations)

2.2 Defining an Autonomous Vessel

A universally agreed term has yet to be specified for an autonomous vessel, as the variations in autonomy level make defining a term more complicated. The International Maritime Organization (IMO), a specialized agency within the United Nations, has a senior technical body known as the Maritime Safety Committee (MSC) who have generated the term Maritime Autonomous Surface Ships (MASS), also known as autonomous vessels or unmanned surface vessels. These vessels are described as ships that operate remotely under semi or fully autonomous control or, to a varying degree, can operate independently of human interaction (IMO, 2018).

The European Commission funded the *Maritime Unmanned Navigation through Intelligence in Networks* (MUNIN) project launched in 2012, which functioned to investigate how autonomous and unmanned vessels can be a key component of a sustainable and competitive European shipping industry. The main objective of the MUNIN project was to show the feasibility of an autonomous and unmanned vessel. This was completed by developing an autonomous ship concept. MUNIN adapted the Waterbourne TP (2011) definition of an autonomous ship, which is described as a vessel with:

Next generation modular control systems and communications technology [that] will enable wireless monitoring and control functions both on and off board. These will include advanced decision support systems to provide a capability to operate ships remotely under semi or fully autonomous control.

Both definitions highlight that the autonomous control can either be either semi or fully autonomous. A comparison of the autonomy scales is mentioned in 2.2.2. A conceptual design developed by Rolls-Royce of an autonomous container vessel is shown in Figure 7.

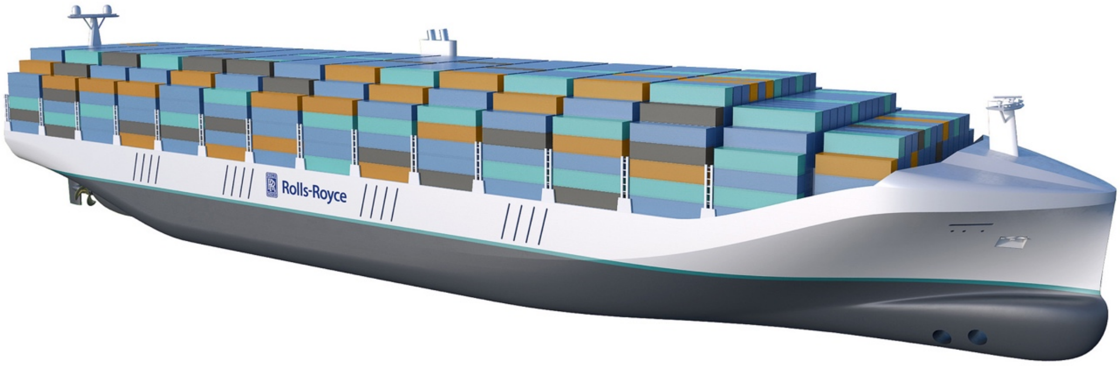

Figure 7: Autonomous Vessel Concept (Rolls-Royce)

2.2.1 How Autonomous Vessels Operate

Autonomous vessels are predicted to be navigating waters by 2028. They differ from traditional vessels in that they operate with fewer crew members "who control an increasing number of autonomous functions and operations on board, possibly from remote control stations" (WMU, 2019). First, autonomous vessels are predicted to maneuver in restricted regions like inland waterways, national waters and neighboring countries, or in special trade areas with onshore central operation centers (WMU, 2019). At a later stage, they will expand to deep sea operations.

Figure 8: Remote Operating Centre (Rolls-Royce)

Figure 9: Remote Operating Centre (Rolls-Royce)

An existing example of an autonomous vessel is Kongsberg's YARA Birkeland, the world's first fully electric vessel, zero-emission, autonomous container feeder concept. It has the capacity to carry 120 twenty-foot equivalent units (TEU) and has a service speed of 6 knots. This year there will be testing of the vessel's autonomous capability, with an intention to move to a fully autonomous operation by 2022. This advance could revolutionize the shipping industry by encouraging the use of zero CO_2 alternatives.

The vessel is planned to initially operate in a remote-controlled manned state, then will progress to a remote control-unmanned phase and finally to an autonomous-unmanned operation. Essentially the vessel will move from decision-support to decision taking (WMU, 2019).

Figure 10: Yara Birkeland (Kongsberg Maritime)

Rolls-Royce Marine remains as one of the leading corporations examining the future of autonomous ships and developing specifications. The Rolls-Royce Marine Advanced Autonomous Waterborne Applications (AAWA) Initiative ended in 2017 and was funded by TEKES (Finnish Funding Agency for Technology and Innovation). In a White Paper from 2016 the company stressed that the technologies required to make MASS "a reality already exist [but] the challenge is to find the optimum way to combine them reliably and cost effectively" (Rolls-Royce, 2016).

The company has even predicted a timeline for remote and autonomous vessel development, including an ocean-going vessel, subject to regulation of course. In fact, Rolls-Royce and Svitzer have collaborated in 2017 to demonstrate the world's first remotely operated commercial vessel, displaying that autonomous vessels can impact the future of maritime operations significantly.

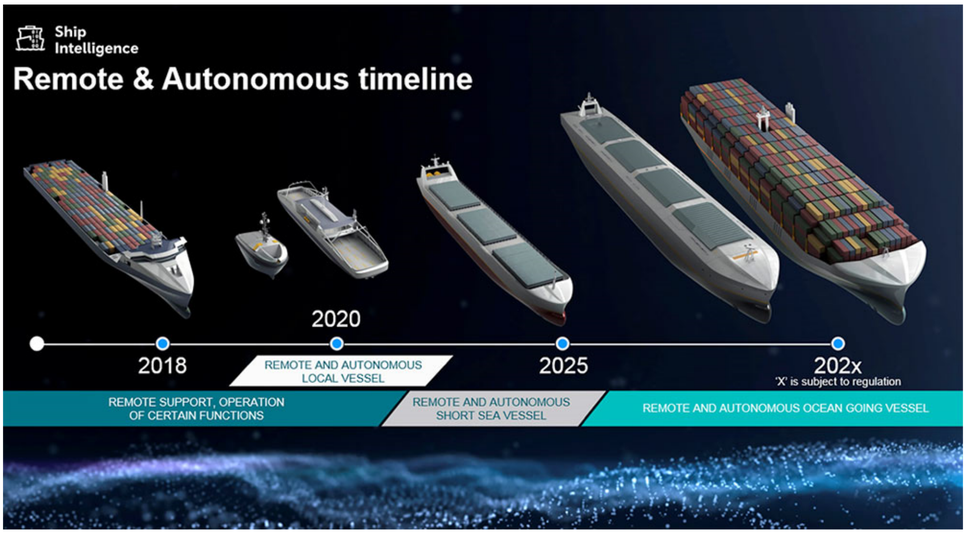

Figure 11: Remote & Autonomous Vessels Timeline (Rolls-Royce)

2.2.2 Defining the Automation Level

To further investigate the impacts of autonomous vessels, a definition of the automation level is required. There are many credible sources that have outlined various automation levels which will be explored in the following sections.

2.2.2.1 The Society of Automotive Engineers (SAE)

The most widely recognized for motor vehicles is from The Society of Automotive Engineers (SAE) International. The guide has been used for motor vehicles but can also be considered as a reference for a vessel's autonomy levels.

SAE has defined various levels of motor vehicle driving automation which has been adopted by the United Nations and the United States Department of Transportation. All the autonomy levels describe the system, including the amount of driver interference needed, and *not* the vehicle characteristics.

LEVEL	AUTOMATION TYPE	EXAMPLES	WHERE OPERATIONAL	IF AUTOMATION STOPS WORKING
	Driver performs part or all of the dynamic driving task			
0	**No driving automation**	No driving automation anywhere	Not applicable (no automation)	Not applicable (no automation)
1	**Driver assistance**	Adaptive cruise control OR lane centering (driver supervises)	Limited roads or modes	Driver resumes performing all of the dynamic driving task
2	**Partial driving automation**	Adaptive cruise control AND lane centering (driver supervises)	limited roads or modes	Driver resumes performing all of the dynamic driving task
	Automated Driving System (ADS) performs all of the dynamic driving task			
3	**Automated driving** CONDITIONAL	Automated driving in dense freeway traffic (low speeds)	Limited area, roads, and/or modes	Driver takes over after warning
4	**Automated driving** HIGH	Automated driving within a city center (geo-fenced location)	Limited area, roads, and/or modes	ADS brings vehicle to safe stop
5	**Automated driving** FULL	Automated driving everywhere	Everywhere on-road	ADS brings vehicle to safe stop

Figure 12: Automation Levels as defined by the Society of Automotive Engineers (SAE)

Additionally, in the below graph, a depiction of the SAE automation levels is displayed:

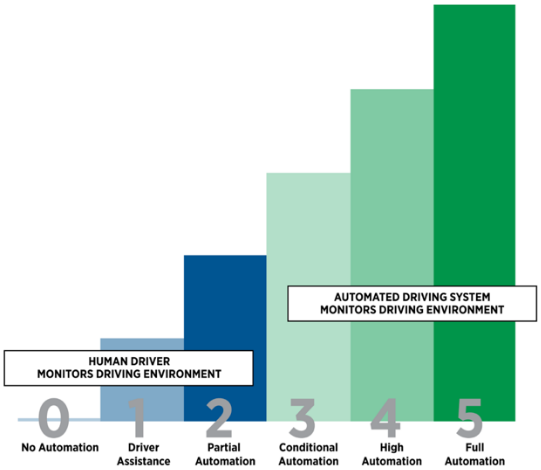

Figure 13: SAE Automation Levels (Graphically)

At the 74th United Nations Road Traffic Safety Forum, there were examples given of what a Level 2 and Level 3 automation would entail. An example of the second level is remote control parking (RCP) and the third level is a highway-pilot that keeps to the lane and can perform lane changes without confirmation by the driver. Also, Level 4 represents a highway function that, upon the driver's command, keeps within the lane and can perform lane changes without any further confirmation by the driver. The system is active from the point the vehicle enters the highway until the pre-defined highway exit (as determined by the driver) and manages all the situations it encounters in this use-case. Before exiting the highway, the driver takes over manual driving before the pre-defined highway exit.

Level 5 signifies a fully autonomous system that imitates the behavior of a human driver, even in situations where the environment is extreme and involves problematic terrains that would prove to be difficult to detect. For this study, the level most closely related to this study is Level 3, describing a vehicle with conditional automation, due to operational speeds being relatively low.

2.2.2.1 *The International Maritime Organization (IMO)*

Furthermore, IMO discussed at the MSC 99th session about the varying degrees of autonomy (non-hierarchically) which could vary over a single voyage. The four levels discussed are outlined in the table below:

Table 2: IMO Definition of Autonomy (IMO, 2018)

Autonomy Degree	Seafarers	Operations
Automated processes and decision support	On board to operate and control shipboard systems and functions	Some operations may be automated
Remotely controlled ship with seafarers on board	On board	Ship controlled and operated from another location
Remotely controlled ship without seafarers on board	None	Ship controlled and operated from another location
Fully autonomous ship	None	The operating system of the ship is able to make decisions and determine actions by itself

The definition that most closely relates to the autonomy degree of a vessel in this study under IMO's definition is the remotely controlled ship with seafarers on board.

2.2.2.1 *Lloyd's Register Group Limited (LR)*

Lloyd's Register Group Limited (LR), a maritime classification society, defined several autonomy levels (AL) adapted from the Lloyd's Register of Cyber Enabled Ships. It was noted that a higher AL could use a lower AL "as part of its reversionary control and a complex system may be a combination of multiple systems at different levels". The autonomy level in this study is most closely related to AL 4.

Table 3: LR Autonomy Levels

Autonomy Levels	Seafarers	Definition
AL 0	Manual: No autonomous function	All action and decision-making performed manually (n.b. systems may have level of autonomy, with Human in/ on the loop.), i.e. human controls all actions.
AL 1	On-board Decision Support	All actions taken by human Operator, but decision support tool can present options or otherwise influence the actions chosen. Data is provided by systems on board.
AL 2	On and Off-board Decision Support	All actions taken by human operator, but decision support tool can present options or otherwise influence the actions chosen. Data may be provided by systems on or off-board.
AL 3	'Active' Human in the loop	Decisions and actions are performed with human supervision. Data may be provided by systems on or off-board.
AL 4	Human on the loop, Operator/Supervisory	Decisions and actions are performed autonomously with human supervision. High impact decisions are implemented in a way to give human Operators the opportunity to intercede and over-ride.
AL 5	Fully autonomous	Rarely supervised operation where decisions are entirely made and actioned by the system.
AL 6	Fully autonomous	Unsupervised operation where decisions are entirely made and actioned by the system during the mission.

2.3 Benefits and Challenges of Autonomous Vessel Use

In this section, an overall discussion of the potential benefits and challenges of autonomous vessel use is presented.

2.3.1 Potential Benefits of Autonomous Vessel Use

Following in the footsteps of self-driving cars and "drones", MASS are presently used for various maritime operations in the defense sector. With technological advancements and an ever growing need to hold safety and environmentally friendly methods to the utmost, the objective has developed to transport both passengers and cargo in the future.

The same benefits associated with a traditional vessel apply, including the ability to transport goods with heavy weight, the capacity is higher than many other forms of transportation and the cost to transport goods should remain inexpensive.

There are many benefits associated with the use of autonomous vessels, including the decreased possibility of maritime accidents, which in turn would increase safety. For example, there is a possibility to monitor hull stress in bad weather conditions by using sensor technologies, which will be able to provide real-time information on the structural integrity of a vessel. Currently, 75 to 96 percent of maritime incidents are caused by human error, a problem that could be eliminated almost entirely using MASS but may be replaced by cybersecurity or technological losses. (Allianz, 2018). Although the chance of human error won't be completely removed when monitoring from a control center, there are better safety measures that deliver greater productivity and efficiency.

Although water transportation remains the most fuel efficient and environmentally friendly method to transport commodities, MASS could go one step further and offer a zero-emission technology by using alternative fuel sources, (UNCTAD, 2018) like batteries and hydrogen fuel cells. Little to no ballast will be required to improve vessel stability, so the risk of water pollution on a marine environment will be minimized. This is due to the superstructure containing accommodation and storage areas being reduced, because a limited human presence is required onboard the vessel with construction costs and crew member costs being reduced as well. The European Commission funded the Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project (Kretschmann et. al, 2015) launched in 2012 which mentions several factors that would make an autonomous vessel a sustainable choice for waterborne transport. Including the ability to slow steam, which reduces fuel consumption and emissions, and operate a ship more efficiently, in turn reducing greenhouse gas emissions

Piracy is another beneficial factor to consider with MASS. With little to no crew onboard the vessel, there will be a decreased risk of the crew being taken for ransom, which may affect the insurance claims associated with crew members. Around major shipping routes like in the Middle East near the Yemeni coast, there is an increased risk of piracy. This was an observed in the increase in the amount of Somalia pirate attacks in 2017 as well (Allianz, 2018). MASS can be used in many of the same ways as a traditional vessel.

2.3.2 Potential Challenges of Autonomous Vessel Use

There are multiple factors that must be addressed when considering the operation of MASS, including accountability and safety. A major challenge, not only for humanitarian works, will be the need to develop a legal framework that considers the ship operation in semi and fully autonomous conditions.

The IMO's MSC announced at their 99th meeting in May of 2018 a regulatory scoping exercise evaluating the most appropriate way to address MASS operations, considering the human element, technology and operational factors (IMO, 2018). This illustrates the first initiatives of the maritime sector to acknowledge the technological advancements regarding autonomous vessels. In this scoping exercise, there are several international maritime conventions that must be addressed, including safety coverage (SOLAS), collision regulations (COLREG), search and rescue (SAR) and the training of seafarers and fishers (STCW, STCW-F).

Another element to consider is the role of a master and crew on board and how it will affect many of the maritime laws and regulations already in place. This will need to be assessed and redefined, including jurisdictional, technical and liability rules (UNCTAD, 2018) that have governed much of the shipping industry for years. The lack of crew on board may pose significant risks to safety as well, due to

In addition, guidelines should be developed specifically for the humanitarian sector regarding autonomous vessel use during a complex emergency or disaster. Many of the countries where WFP discharges cargo do not have the proper legal structures in place to handle the use of MASS and will need to be approved by both the local and national government. This factor could prove to be particularly challenging as this will be on an emergency basis and for future operations there will need to be country protocols in place to allow for long-standing approval. In fact, The UK Maritime Autonomous Systems Regulatory Working Group (MASRWG) recently published the first industry Code of Practice for autonomous vessels in November 2017, providing guidance for the design, operation and construction of MASS (Hellenic Shipping News Worldwide, 2018).

Inevitably, the traditional marine liability insurance will need to be developed for MASS technology and must consider possible collision claims, cargo losses, piracy situations and war risk, the latter two which may be more prevalent at the discharge ports in which WFP operates. A beneficial addition to MASS would be a security system that has the ability to transmit security alerts and the GPS location to the appropriate authorities when a vessel is under threat (UNCTAD, 2018).

With increasing technology, there is also an increased risk of cybersecurity attacks. To better prepare for these circumstances, in 2017 IMO updated two general security management codes in the International Ship and Port Facility Security (ISPS) code and International Safety Management Code (ISM) to reference cybersecurity and made it a requirement for operators to consider the risks when performing operations (ISPS, 2014). Both codes are international standards within the International Convention for the Safety of Life at Sea (SOLAS). Although the modifications do not take effect until January of 2021, risk management continues to be a growing concern in the maritime sector. Especially with the mixed vessel use and varying ages of computer systems, some outdated.

2.1 Emergency Humanitarian Response with Unmanned Vehicles

In this chapter an existing method for emergency humanitarian response with unmanned vehicles is presented. The pros and cons of its use is discussed, along with examples of the technology in action. Afterwards, the potential humanitarian uses for autonomous vessels is discussed.

2.1.1 Existing Methods

Advancements regarding the use of another technology, Unmanned Aerial Vehicles (UAVs) or "drones" for humanitarian response has steadily increased in recent years (OCHA, 2014). Also known as remotely piloted aircraft, they can fly both autonomously and remotely and have already been used in Haiti and the Philippines by humanitarian organizations. As predicted with autonomous vessels, UAVs have proven to be a significant challenge to implement due to the need for specific guidelines that promote good practice and ensure privacy and data security. With that being said, they also can be used as a low cost alternative and a valuable tool in providing assistance in complex humanitarian emergencies (World Food Programme Insight, 2018).

Although these "drones" are already in use for humanitarian work and disaster response, their uses are ever evolving as technology matures. The main uses are for data collection and observation, and logistics and package-delivery, the former being the most prevalent. Not only can UAVs be used for real time information and situation monitoring, but there is also interest in using them for search and rescue efforts, equipping each with an infrared or specialty camera, and using imagery or videos to function as a before and after monitor for damage assessments.

Figure 14: UAV in Humanitarian Reponses – Photo: WFP/Laura Lacanale

In one case study, UAVs were used to assess the damage in the Philippines after Typhoon Haiyan. With agreement from the Mayor of Tacloban, they were used to check the damage from storm surge, flooding and if roads were passable. In fact, the International Organization for Migration (IOM) has used several different UAVs over the years to support relief activities and to assess damage, prevent and reduce disaster risks.

The concept of using UAVs for the delivery of in-kind goods and medical supplies has risen as well. Although no proof has been made that "drones" are more efficient than traditional logistics and delivery systems. Services like the United Nations Humanitarian Air Service are more cost-efficient and can carry larger shipments.

The challenges of implementing UAVs involve privacy and data protection as well as legal and regulatory issues. In fact, the Humanitarian UAV Code of Conduct (UAV Code, 2017) has been in development since 2014 and describes the best practices involved in the safe use of civilian drones. It has been edited by over 60 organizations and describes how "drones" should be used to support humanitarian efforts, whether in a natural disaster or armed conflict, by making sure the required national laws are followed and safety and transparency are prioritized.

2.1.2 Potential Humanitarian Uses of Autonomous Vessels

The use of MASS for humanitarian purposes has not been implemented at this stage, however it will match many of the traditional vessel uses in terms of cargo and passenger movements. There are no limitations technologically on the ability of MASS to function as a reasonable means of deep-sea transport, it just has yet to be done.

MASS will allow freight to be transported over long-distances to remote areas with limited infrastructure. The options most closely associated with a humanitarian application is the need to carry cargo or for passenger ferrying use, while other applications could be for oil spill response and marine salvage (UNCTAD, 2018).

No humanitarian organizations have commenced using MASS, but there are many research efforts presently to analyze the challenges of remote and autonomous shipping operations. Additionally, MASS can be used to deliver in-kind goods, move passengers and other commodities, and maybe in the far future be used as a search and rescue vessel, or possibly to relocate populations of civilians from a disaster zone.

In developing economies, the impact of automation is more attenuated than in more advanced economies and will required extensive investment in education, infrastructure, training and research to bridge the digital divide (WMU, 2019). There will need to be technologies developed specifically for humanitarian response, however.

3 Methodology

In the following section, the process for the shipping cash flow model and emissions analysis will be summarized:

3.1 Financial Analysis

For analyzing the operation costs the following steps referencing the shipping cash-flow model will be completed:

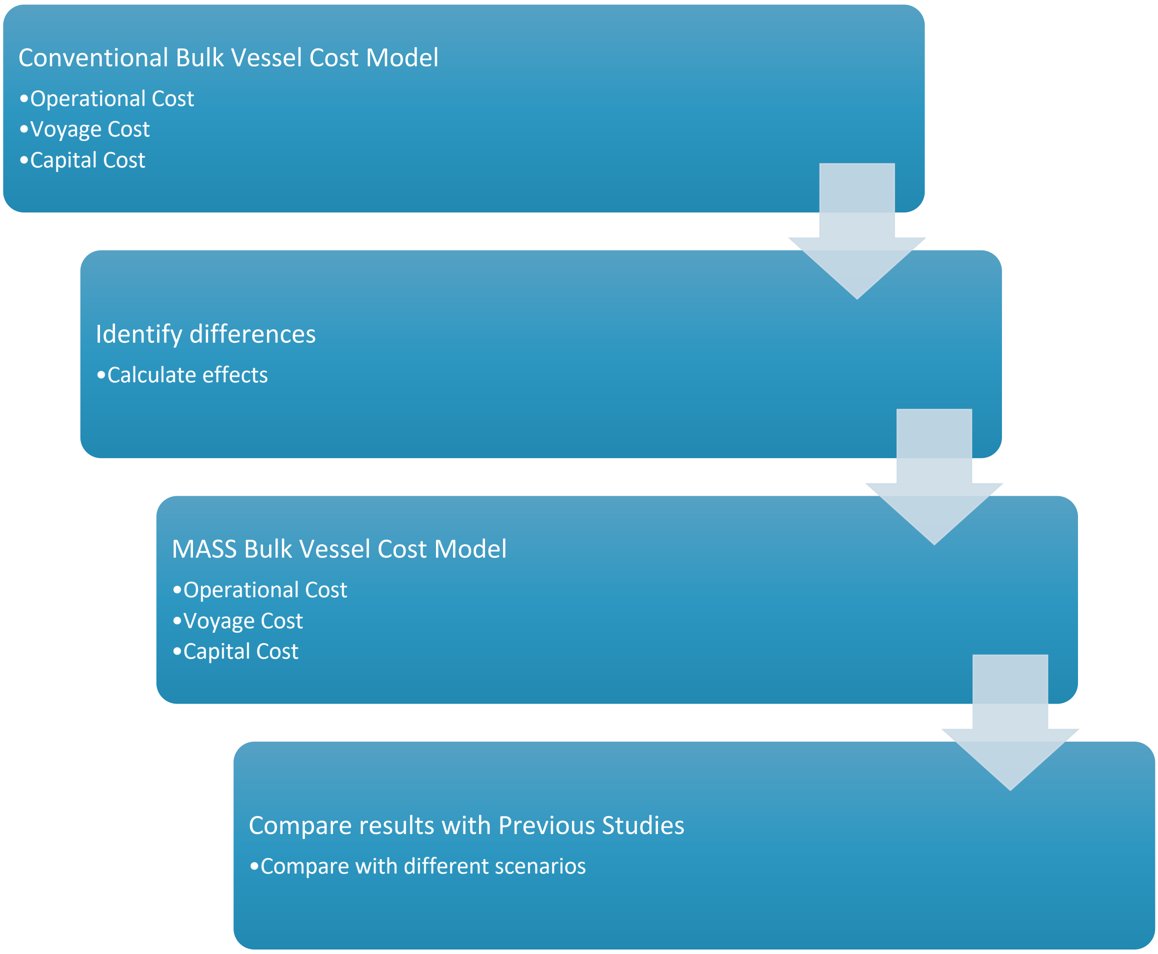

Figure 15: Financial Analysis Steps

3.2 Emissions Analysis

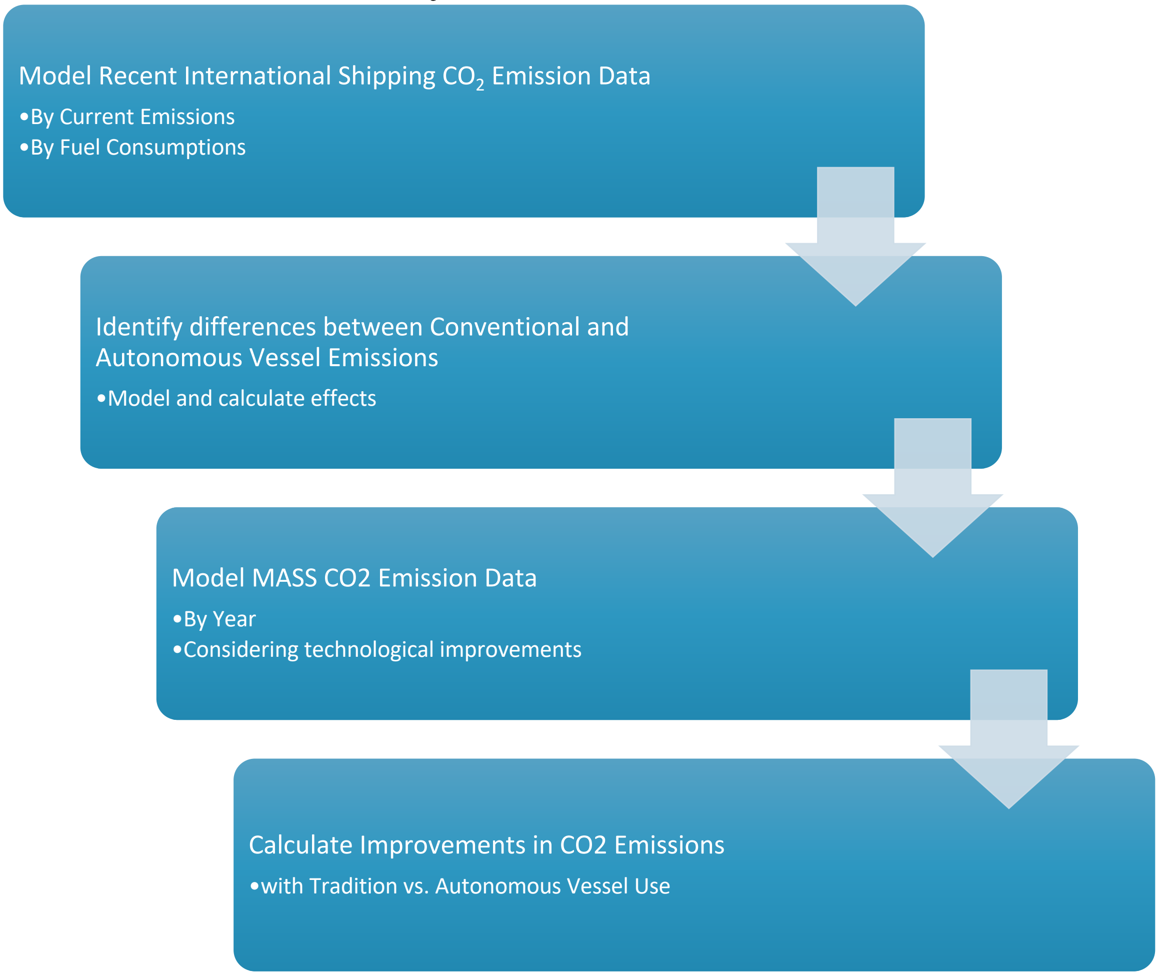

Figure 16: Emission Analysis Steps

4 Traditional versus Autonomous Vessels

In this section, a comparison of economic and environmental benefits and drawbacks are discussed for a traditional and autonomous vessel. A summary of maritime transportation costs is presented from a larger context. Then, the design vessel used in this thesis to estimate the impacts of MASS is reviewed and related to the shipping cost model. This model describes the vessel costs to be studied which include the operating, voyage and capital costs and will be used as the foundation for the traditional and autonomous bulk vessel comparisons. Afterward, the environmental implications of the shipping sectors greenhouse gas emissions are discussed, with estimations for how the carbon dioxide emissions could cultivate if regulations aren't put into place immediately. Using the current emissions data, a discussion of the ecofriendly benefits of autonomous vessel use is communicated and related quantitatively to conventional vessel use.

4.1 Maritime Transportation Costs

Maritime transportation costs vary depending on a multitude of determinants, including port tariffs, the commodity shipped and the vessel operating costs. To expand on some of the factors detailed in Figure 17, vessel operating costs have decreased in recent years due to technological advances allowing an increase in fuel efficiency. In addition, port operation automation has improved the financial burden and decreased environmental expenditures.

Although maritime transport is seen as a cheaper solution to transport commodities, there are a few important points to note. The first is that when commodities travel over longer distances more fuel and time is required, meaning the operating and capital costs will increase, respectively. There is minimal correlation between the travel distance and freight costs and is more influenced by the liner shipping connectivity index indicating (UNCTAD, 2015).

The liner shipping connectivity index (LSCI) indicates a country's integration level into global liner shipping networks. This is vital because a countries' access to world markets depends largely on their transport connectivity. Particularly with regards to regular shipping services for the import and export of manufactured goods. The LSCI is produced from five elements: the number of ships, the total annual container-carrying capacity of those ships, the maximum vessel size, the number of services and the number of companies that deploy container ships on services to and from a country's ports. (UNCTAD, 2018). For example, in 2018 China had a LSCI of 187.78, indicating the largest connection to other shipping networks in the world.

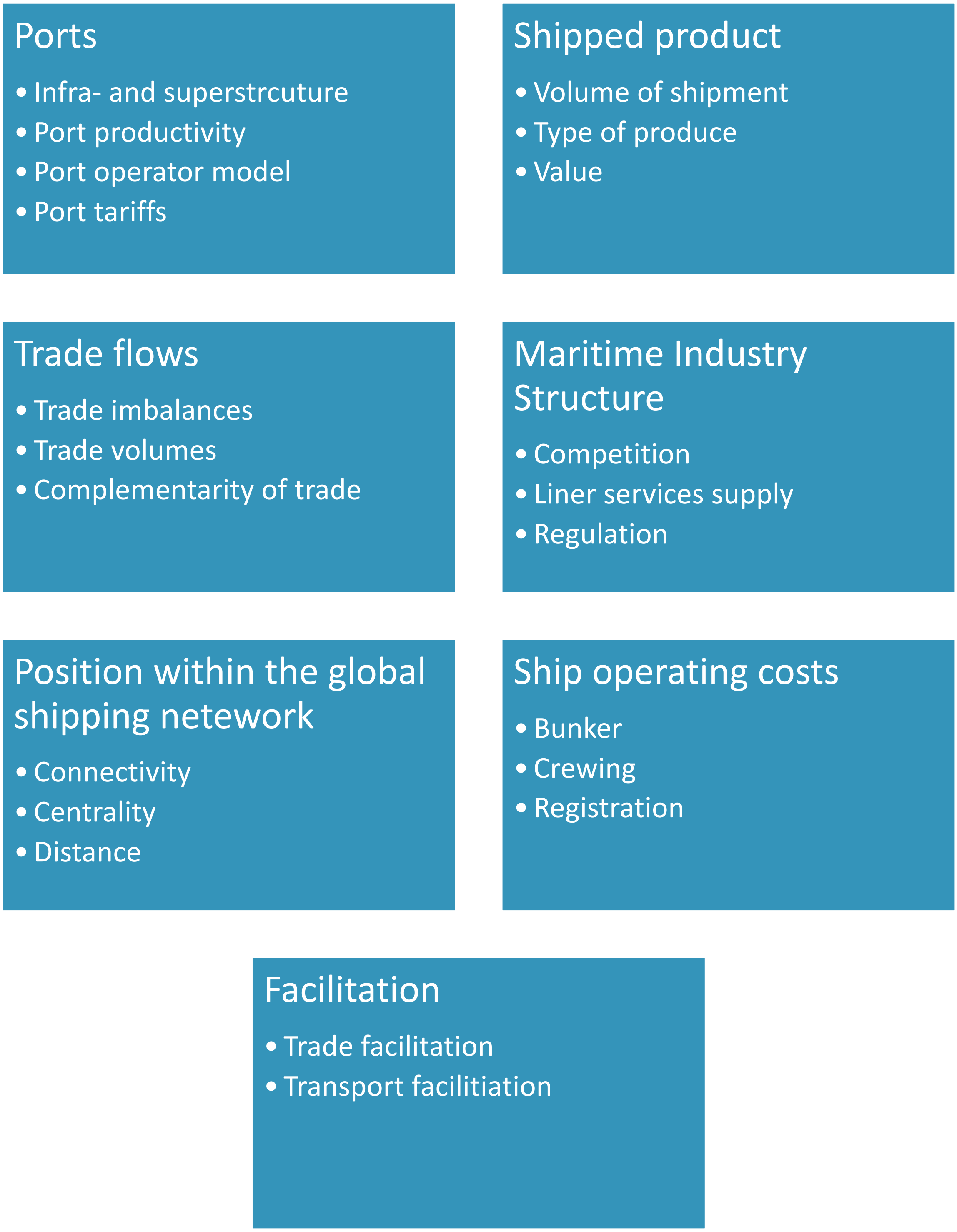

Figure 17: Determinants of Maritime Transport Costs (adapted from Wilmsmeier et al., 2014).

The most relevant factors associated with this thesis are the ship operating costs and voyage costs detailed in the following sections.

4.1.1 Design Vessel

Bulk carriers are one of the most widely used vessels within the global merchant fleet and can transport bulk cargo without the use of bags or containers. The design vessel referenced in this thesis will be a Handymax dry bulk carrier, which is one of the three dominating types of bulk carriers in the fleet.

Deadweight tonnage (DWT) expresses a ship's carrying capacity in metric tons (1,000 kg), including the weight of bunkers and supplies necessary for the ship's propulsion. There are typically four subcategories for bulk carriers grouped by their DWT including the Handysize (10,000 – 35,000 DWT), Handymax (35,000 – 55,000 DWT), Panamax (55,000 – 80,000 DWT) and Capesize (80,000+ DWT) (MAN Diesel & Turbo, 2014).

Commonly, the vessels diesel engines are powered by heavy fuel oil (HFO) and marine diesel oil (MDO). HFO is the main marine fuel used nowadays and has a very competitive price, but high environmental impacts. MDO is composed of lighter distillate fractions than residual fuel and has lower sulfur content (Lloyd's Register & University College London, 2014), making it a more environmentally friendly option.

As stated formerly, the design vessel is a Handymax, a large bulk carrier and based on a vessel built by Brodosplit, a shipyard located in Split, Croatia. The main vessel design characteristics shown in Table 4 will be used to compute the costs and environmental impacts associated with a traditional and autonomous vessel of its same magnitude. To serve as a visual aid for the design vessel, there is a generic plan showing the typical layout of a geared Handymax Bulk Carrier in Figure 18, the layout provided by Brodosplit for the reference vessel in Figure 19, and a photo of the design vessel in Figure 20.

Table 4: Design Vessel Characteristics (Brodosplit, 2014).

Length over all (m)	189.99
Length between perpendiculars (m)	182.00
Breadth (m)	32.24
Depth (m)	17.00
Design Draft (m)	11.00
Deadweight (t)	45500.00
Main engine (kW)	8580.00
Auxiliary Engine (kW)	3 x 680.00
Trial speed at design draft (kn)	15
Cargo holds	5
Cranes	4
Crane lifting capacity (t)	35

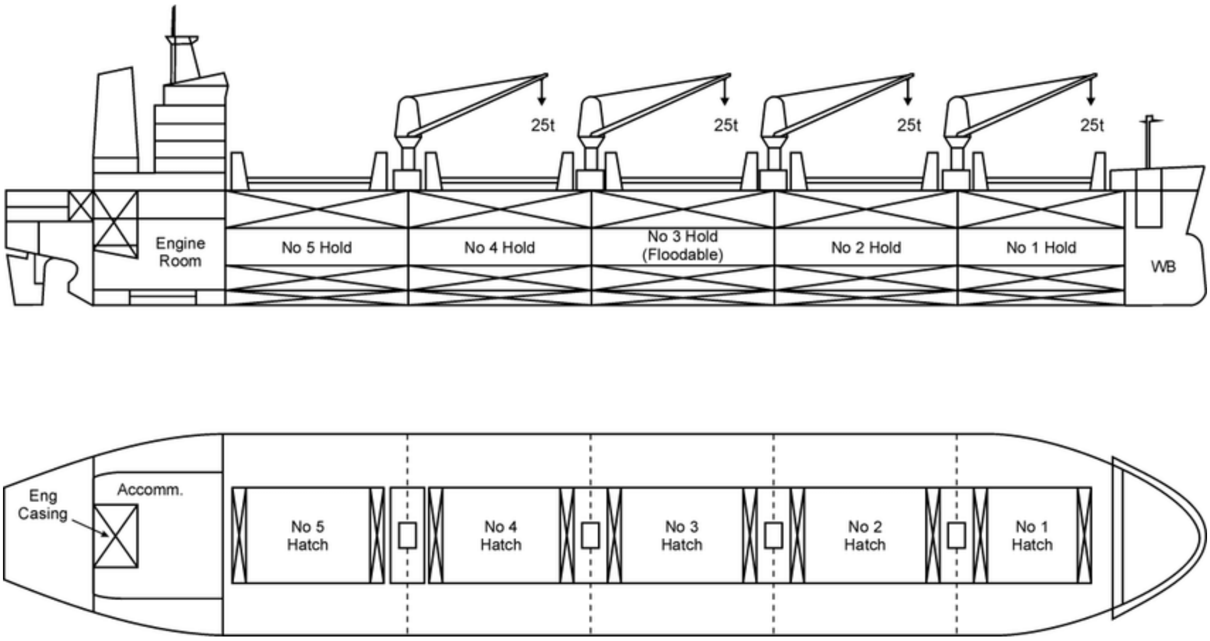

Figure 18: Generic Plan of a Geared Handymax Bulk Carrier (Akyar, 2018).

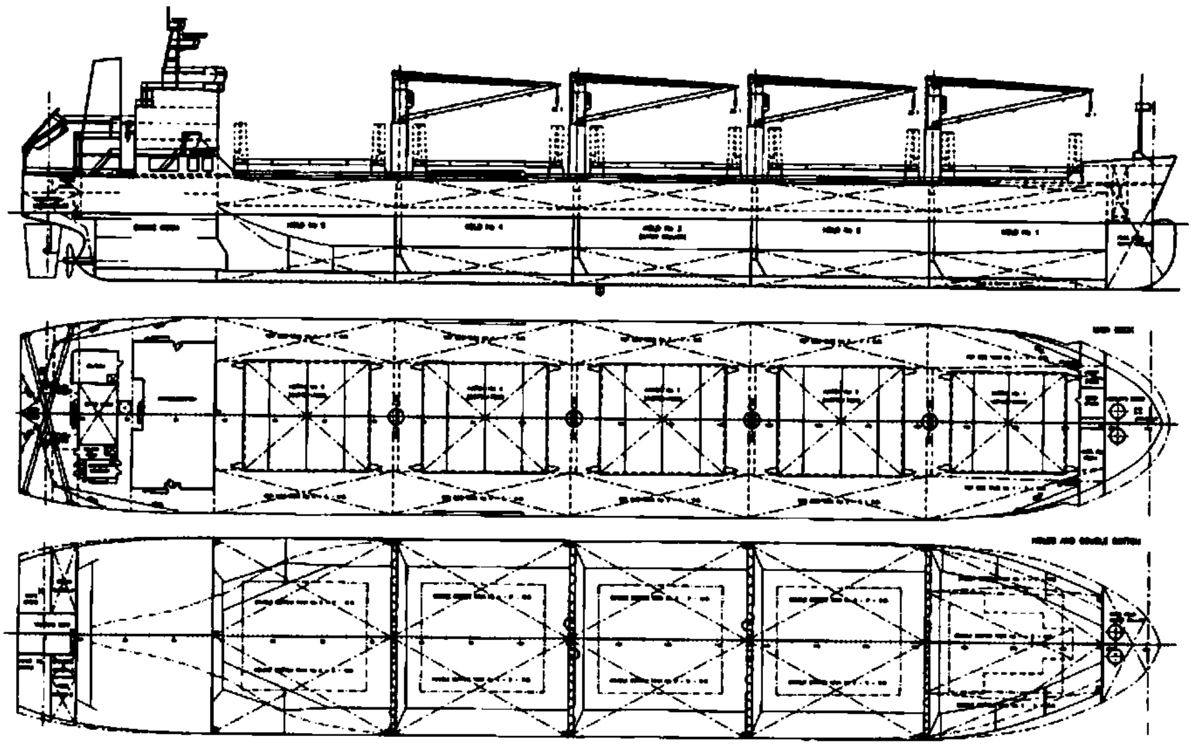

Figure 19: Plan of Referenced Handymax Bulk Carrier (Brodosplit).

Figure 20: Example Handymax Bulk Carrier (Equinox Maritime)

4.1.2 Vessel Cost Elements

With all modes of transportation, the goal is to move commodities in the most efficient and economical way, so it is a necessity to balance costs accordingly. Survival in the shipping market is crucial for shipowners, so the financial performance of a vessel must be managed closely by working with a few key variables: the ship running costs, the revenue received from chartering or operation of the ship and the method for how the business is financed (Stopford, 1997).

The shipping cash-flow model in Figure 21"describes how revenue is generated by a ship and after costs are deducted, creates free cash flow which is used to cover taxes, pay dividends and generate a profit for the shipowner" (Kretschmann et. al, 2017). This model implies that the free cash flow of a vessel is created by the ship revenue which depends on the cargo capacity, ship productivity, and freight rates. Cargo capacity considers the ship size, bunkers and stores, and ship productivity involves the operational planning, speed, port and off-hire time (Stopford, 1997).

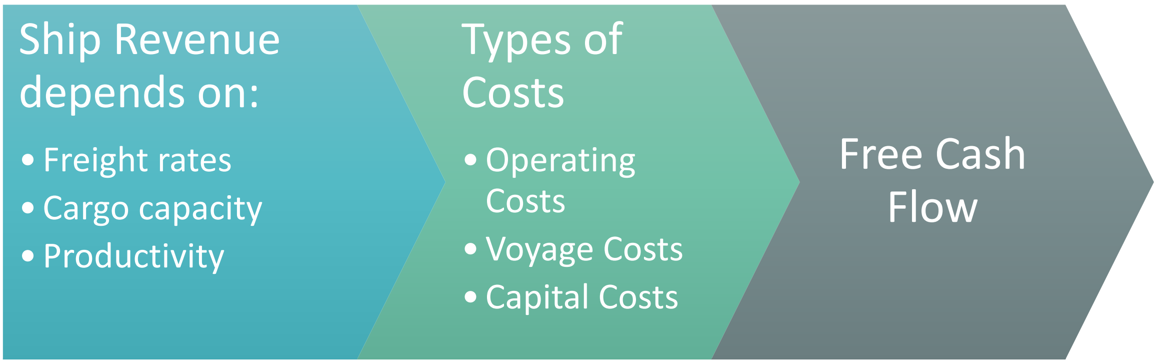

Figure 21: Shipping Cash-Flow Model (Adapted from Stopford, 1997).

The MUNIN deliverable will be heavily referenced for this section of the report due to it being an existing in-depth assessment for the economic viability of an autonomous ship. In the report, the shipping cash-flow model is used with the intention to describe why it is appropriate to focus on the cost associated with an autonomous ship and compare these against the cost of a conventional ship (Kretschmann et. al, 2015).

In the methodology of the study it is worth mentioning that for the two ships the potential to generate revenue over the assumed vessel lifetime of 25 years is identical, therefore the resulting vessel indicating the higher cash flow would be more favorable. A further financial analysis evaluates the net present value (NPV) of the autonomous and conventional bulker using a yearly operational profile. The ship referenced in the quantitative analysis of the report is a Panamax dry bulk carrier, a larger class of vessel than the design Handymax vessel in this study. Several of the same procedures shown in the MUNIN report will be applied for the thesis design vessel.

The methodology behind this analysis involves using a similar shipping cash-flow model as pictured in Figure 21 to approximate costs associated with an autonomous vessel excluding analysis of the revenue. Considering both the traditional and autonomous vessel will perform the same tasks, an assumption can be made that they will have similar economic structures and the same nature of costs will apply for both vessels.

The most relevant components of the cash-flow model for this report are the operating, voyage and capital costs. These will be the basis for modeling the cost comparison of the two vessels. The autonomous bulk carrier is unique in that the crew will be reduced on board, but a new Shore Control Center (SCC) will need to be established to monitor the vessel and voyage at a cost. Additionally, with new more fuel efficient ship designs, the air resistance will be reduced, decreasing voyage costs.

The many cost variations for the autonomous bulk vessel are summarized in Figure 22 below, where a plus (+) represents an increase in costs and a minus (-) represents a decrease in costs.

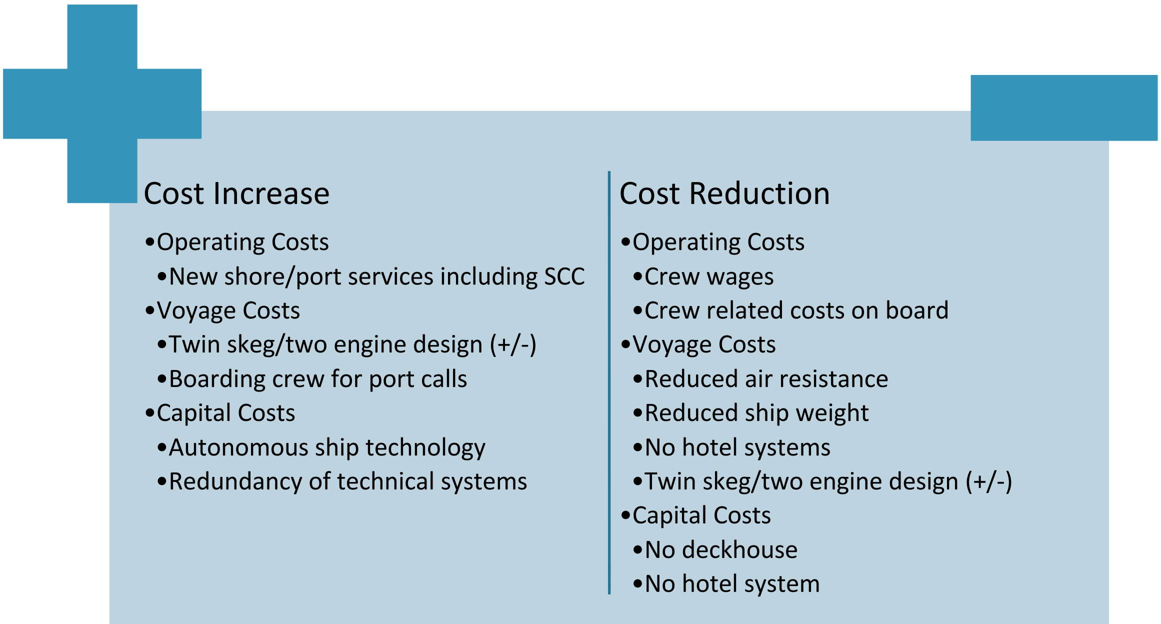

Figure 22: Cost Variations for the Autonomous Bulker (Kretschmann et al., 2017).

Stopford (1997) describes another cost structure model that relates the cost and ship size, usually referred to as economies of scale. Equation 1 below defines the yearly cost per DWT of a ship by adding the operating, maintenance, voyage, cargo handling costs, and capital costs and dividing by the ships DWT.

$$C = \frac{OC + PM + VC + CHC + K}{DWT}$$

Equation 1: Cost per ship dwt (adapted from Stopford, 1997)

Where C is the cost per DWT per annum, OC is the operating cost, PM is the periodic maintenance provision per annum, VC is the voyage costs per annum, CHC is the cargo handling costs per annum, K is the capital cost per annum, DWT is the ship deadweight.

Use of a larger vessel will reduce the unit freight cost, which will, in turn, generate more cash flow for a shipowner. The economies of scale in bulk shipping confirming this fact is shown in Table 5. With a larger ship size and higher DWT, the yearly cost per DWT is lower.

Table 5: Economies of Scale in Bulk Shipping (Stopford, 1997).

Ship size (dwt)	Operating cost (in $1000s)	Bunker cost (in $1000s)	Total cost (in $1000s)	Cost per dwt ($1000s) per annum
30000	1414	680	2095	70
40000	1476	778	2254	56
65000	1633	972	2605	40
150000	1940	1458	3398	23
170000	2120	1620	3740	22

4.1.3 Operational Costs

The operational costs of a vessel consist of all the charges involved with the day-to-day operation of a vessel, such as the crew number and wages, repairs and maintenance and insurance. Additionally, the operating cost structure depends on the size and nationality of the crew, maintenance policy, and the age and insured value of the ship, and the administrative efficiency of the owner. Operation costs usually account for 25% of total costs (Stopford, 1997). Generally, the older a vessel is the more operational costs are required to keep it running. The equation below details the principal components of operating costs:

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

Equation 2: Operating Costs (adapted from Stopford, 1997)

where OC is the operating cost, M is the manning or crew cost, ST represents the cost of the ship stores, MN is routine repair and maintenance, I is insurance and AD administrative costs.

An example of the operational costs for a Capesize bulk carrier vessel is shown in Figure 23 and displays the crew, stores, maintenance, insurance and general costs by the age of the ship. Using the average costs associated for all ship ages, insurance accounts for approximately 37% of the operational costs, followed by the crew cost at 29%. Maintenance, stores and general costs comprise approximately 11-12% each. The insurance costs, in this case, consider the hull and machinery, war risks and protection and indemnity insurance (P&I). The crew costs consist of the crew wages, travel, manning and support, medical insurance and victualling.

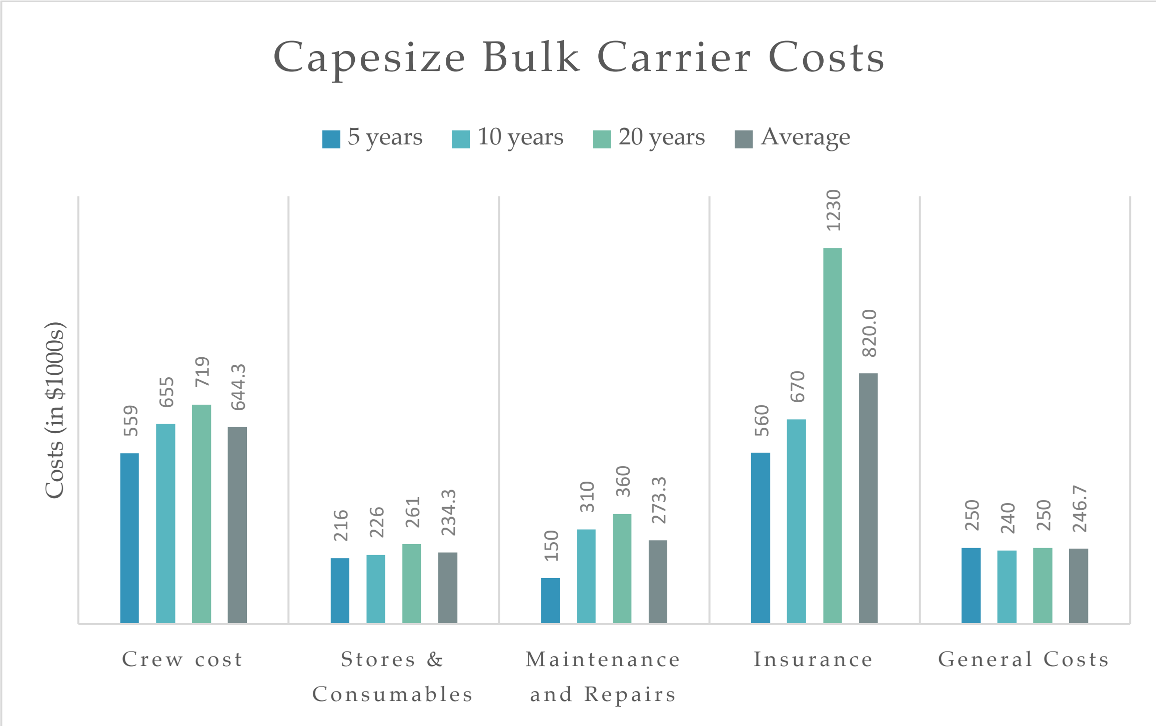

Figure 23: Operational costs of Capesize Bulk Carrier (adapted from Stopford, 1998)

A common assumption about autonomous vessels usage is reduced operational costs due to an increase in technological advances in monitoring sustainable propulsion and software capabilities. This will be discussed in detail in the following sections.

4.1.3.1 Crew Costs

The crew or manning cost is usually the largest portion of the overall operational costs at approximately 42% and "include the basic salaries and wages, social insurance, pensions, victuals and repatriation expenses". In recent years, the degree of automation of mechanical operations has helped to reduce crew numbers as well (Stopford, 1997). IMO resolution A.1047(27) discusses the Principles of Minimum Safe Manning (2011), which considers the cargo to be carried, the size and type of ship, the maintenance method used, the construction and equipment of the ship, and most importantly in this study, the level of ship automation. All these factors calculate the crew composition and size so that the tasks onboard can be performed safely.

MASS use means there will be a possibility to reduce the number of crew on a vessel by replacing these individuals with a more automated technology means. The short-term benefit doesn't necessarily outweigh the capital costs to construct the ship, however. Over the years in the shipping industry, the number of crew required on a ship has decreased but has approached approximately a standstill in the past half-century. As MASS begins to operative more efficiently the crew size will most likely decrease even further.

The MUNIN study estimates an average savings of USD 945,000 per year on the crew wages and associated costs with travel, victualing, etc. Additionally, an estimated USD 23,000 average savings per year by reducing general stores like medical, cabin, safety, and protective equipment, as well as another USD 44,000 savings associated with the hotel system on board (heating, air conditioning, etc.) (Kretschmann et al, 2015). A correlation adapted from the MUNIN study is shown in Figure 24

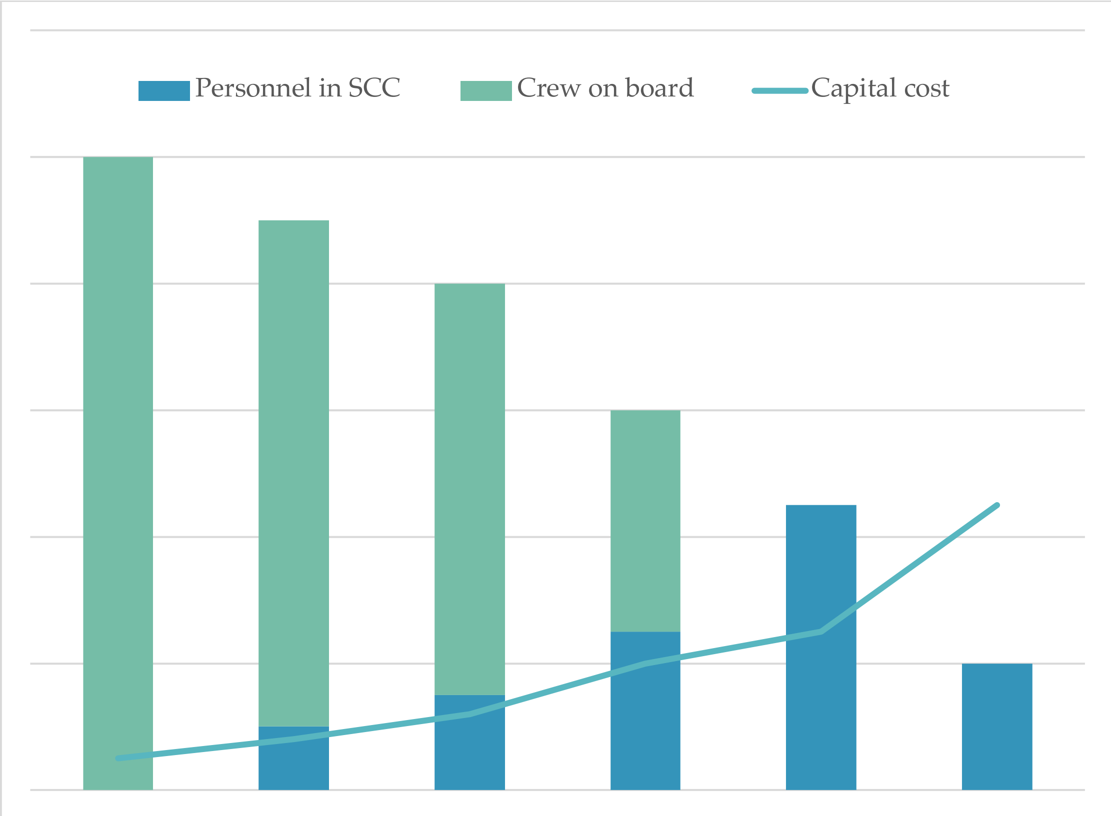

Figure 24: Principal Correlation between crew size and new building cost (adapted from Kretschmann et al, 2015).

As the number of crew on board decreases, there is a projection that more personnel will be in the SCC and capital costs will increase for the autonomous vessel.

4.1.3.1 Shore based Control Center (SCC)

A new concept unique with autonomous vessels use is the shore-based control center (SCC). The crew size will decrease on board the vessel and increase on land in an SCC which will need to include additional costs for staff wages, rent, equipment, etcetera. An overall scheme of the employment plan for the SCC from the Kretschmann et. al (2015) study is shown in Table 6 and was adapted from wage information from the International Transport Workers' Federation (ITF) Uniform Total Crew Cost ("TCC") Collective Agreement in 2014. Each role is matched with an ITF equivalent to approximate shore control center costs per year.

In the study, there are two departments, one with continuous 24/7 operation and another concerning a planning and support division. With this concept, the SCC monitors 90 vessels at once and will need 169 employees to run. The MUNIN project estimates an annual cost for the SCC to be about USD 10.44 million or USD 116,000 per vessel.

Table 6: Employment plan of SCC (adapted from Kretschmann et. al, 2015).

Department A - Continuous 24/7 Operation			
	Per shift	Total number	ITF wage scale equivalent
Operators (1 per 6 vessels)	15	86	3rd Officer
Back up operator (1 per 5 operators)	3	17	3rd Officer
Watch keeping supervisor	3	17	Master
Watch keeping engineer	3	17	Chief Engineer
Watch keeping captain	3	17	Master
Department B – Planning/Support - one shift operation			
Voyage planners		5	2nd Officer
Maintenance planners		5	1st Engineer
Administrative personnel		5	3rd Officer

Furthermore, according to the MUNIN report, there is an estimated investment cost of USD 2.1 million if the equipment is replaced every three to thirteen years, and approximately USD 873,957 per year of operating costs for training, software and power supply that should be considered.

4.1.1 Voyage Costs

The voyage costs of a vessel consist of fuel costs, port dues, tugs, pilotage, and canal charges. Voyage costs usually account for 40% of the total costs (Stopford, 2009), and varies for each specific journey a vessel makes. The costs are variable and change with each specific voyage a vessel makes. The equation below details the major components involved when computing voyage costs:

$$VC = FC + PD + TP + CD$$

Equation 3: Voyage Costs (adapted from Stopford, 1997).

where VC represents voyage costs, FC is the fuel costs for main and auxiliary engines, PD port and light dues, TP is the tugs and pilotage, and CD is canal dues.

For autonomous vessels, there is a likelihood that there will be reduced air resistance with fewer facilities for accommodation on board and new fuel-efficient ship designs. The lighter ship weight will be advantageous and an estimated potential fuel savings of 12 to 15 percent (Kretschmann et. al, 2015) could be possible. For this study, only the costs of the fuel for the main engine will be considered.

4.1.1.1 Fuel Costs

The fuel price is the largest component of voyage costs at approximately 47%. Fuel costs can fluctuate over time and are the most unpredictable component involved in computing the cost of a journey. "The fuel a ship burns depends on its design and the care with which it is operated" (Stopford, 1997), so it is becoming increasingly important for ships to improve both the fuel efficiency and energy consumption.

Likewise, a ships fuel consumption depends on the operational speed and the design of the hull. A speed reduction, sometimes identified as "slow steaming", will result in fuel savings because of the reduced water resistance (Stopford, 1997) and because the fuel consumption is proportional to the design speed of a vessel. This relationship is shown in the equation below:

$$F = F^{*}(S/S^{*})^{a}$$

Equation 4: Fuel Costs (adapted from Stopford, 1997).

where F is the actual fuel consumption (tons/day), S is the actual speed, F* is the design fuel consumption, and S* is the design speed. The exponent a varies depending on the engine used: approximately 2 for steam turbines and 3 for diesel engines.

The price of bunkers fluctuates frequently as seen in Figure 25 which depicts the price per metric ton of IFO 80 and MGO from early 2016 to early 2019. It is not possible to forecast the price of fuel in the future, so for this study, there will be assumptions made for the costs of MDO and IFO, "a blend of MGO and HFO, with less gasoil than MDO" (Anton Paar).

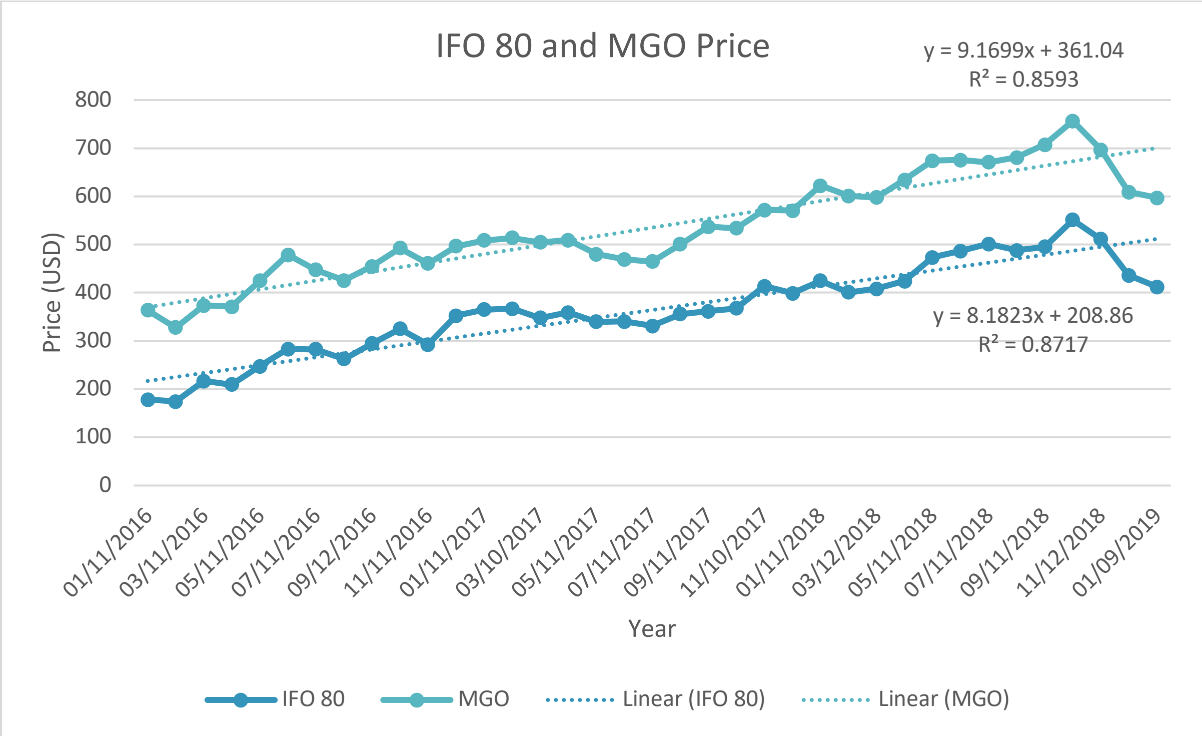

Figure 25: Bunker Prices (Ship & Bunker, 2019).

Fuel costs are influenced by the weight of the ship and with autonomous vessels, there will be a new lighter ship design which will increase the fuel efficiency. For this thesis, the reference fuel price will consider the vessel running on only MDO, a blend of MGO and HFO, "due to high risks and technical challenges for an autonomous operation using HFO as the main fuel… [so the] simplest solution for an autonomous vessel was found to be a distillate fuel oil system" (Kretschmann et. al, 2015).

4.1.1.1 Total Hull Resistance

Another factor that must be taken into account is the total hull resistance, R_T, or the ship's resistance to water when in motion. This force acts against the vessel opposite to its direction of motion and depends on the speed, water characteristics, and ship hull attributes. Adapted from the United States Naval Academy (USNA) lecture, the following formula describes a ship's resistance to motion:

$$R_T = R_V + R_W + R_{AA}$$

Equation 5: Total Hull Resistance (adapted from USNA).

where R_T is the total hull resistance, R_v is the viscous or friction resistance, R_w is the wave making resistance and R_{AA} is the air resistance by the ship experiences when moving through calm air.

Shown in Figure 26, at various ship speeds, different resistances constitute a larger percentage of the total hull resistance. This curve structure is standard for nearly all vessels and the hump is a function of the ships speed and length. At higher speeds, the wave making resistance is more dominant, but at lower speeds, the friction or viscous resistance prevails. The resistance curve can be determined through computer modeling of the ship's hull and solving fluid flow equations related to computational fluid dynamics using the finite element analysis method, not discussed in detail in this report.

After recalling the basic equation for power as force multiplied by velocity, the same can be related to a vessels movement through water. The product of ship speed and total hull resistance is the power needed to propel a vessel through water. Another relation frequently considered is that ship power is approximately proportional to the speed cubed, so if a ship wants to double its speed, it will need almost eight times more power ($2^3 = 8$) (USNA). This increase in power also means that more fuel will be expended, so careful voyage planning is important when moving between ports.

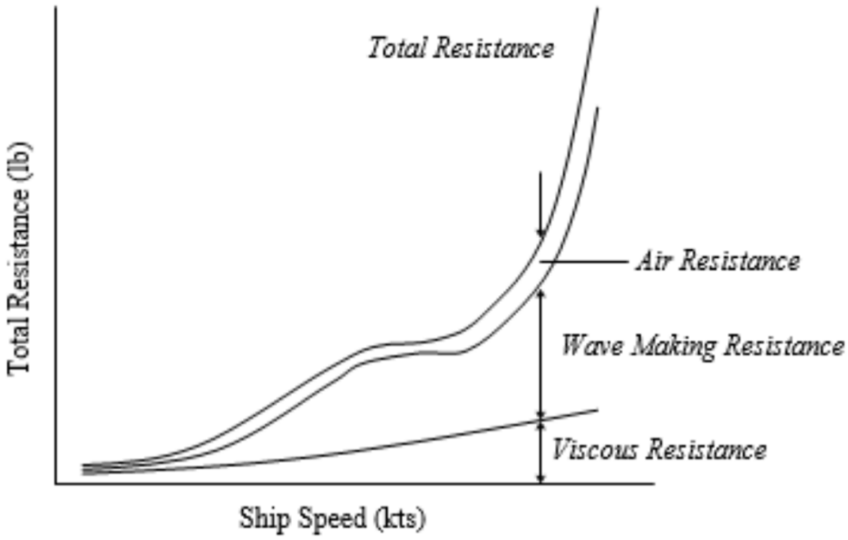

Figure 26: Components of Hull Resistance (USNA).

Knowing the total hull resistance is essential because the value is used to plan the overall power schemes for the vessel when operating at the service or maximum speed. Additionally, R_T can be correlated to the ship's effective horsepower (EHP) which is defined as "the horsepower required to move the ship's hull at a given speed in the absence of propeller action" (USNA), shown in Equation 6:

$$EHP = \frac{R_T * V}{550\frac{ft - lb}{sec - HP}}$$

Equation 6: Effective Horsepower (USNA)

Where EHP is the effective horsepower (HP) , R_T is the total hull resistance in pounds (lbf), V is the ships velocity in feet per second (ft/sec) and the conversion factor of 1 watt is equal to 1/550 HP.

If we simplify calculations and use the air resistance as the value for the total hull resistance, we can model the reduction of propulsion power for an autonomous vessel and compare the results to a traditional vessel at different design speeds. For this study, R_v, the friction resistance and R_w , the wave making resistance will not be studied.

4.1.1.1.1 Air Resistance

A component not considered in Stopford's text, but mentioned in the MUNIN quantitative assessment is the air resistance factor. Air resistance is affected by the shape of the ship above the waterline involving the area of the ship exposed to the air, and the ship's speed through the water. Typically, approximately four to eight percent of the total ship resistance is from air resistance (USNA). The equation for frontal wind resistance is the following:

$$R_{AA} = \frac{\rho}{2} * C_d * V_{app}{}^2 * A_F$$

Equation 7: Air Resistance (Adapted from Kretschmann et. al, 2015).

where R_{AA} is wind resistance, ϱ is the air density, C_d is the wind resistance coefficient, V_{app} is the apparent wind speed and A_F is the ships cross-sectional area over the waterline.

The air density, ϱ is assumed to be approximately 1.225 kg/m^3 which is used at sea level and 15 degrees Celsius (59 degrees Fahrenheit). The wind resistance coefficient assumed for the autonomous dry bulk vessel in the MUNIN study (Kretschmann et al, 2015) is C_d = 0.45, which is recommended for a car carrier with closed fore section

The traditional vessel is assumed to have a C_d equal to 0.68, which is specified for a tanker (Blendermann, 1996). The apparent wind speed, V_{app}, is the summation of the ship speed (15 knots or 7.717 m/s) and the true wind speed (1 knot or 0.5 m/s). The true wind speed is estimated by using the Beaufort wind force scale, which is an empirical measure for describing wind intensity based on sea conditions (Met Office). A selection of force 0 describing calm winds which can be assumed as less than 0.5 m/s or 1 knot for this study.

It is predicted that autonomous vessels will have reduced air resistance, "a lower light ship weight and … [will] no longer need to support a crew living on board". Losing a portion of the ship's superstructure will typically represent approximately 2% of the vessel's total air resistance in calm weather, but could be a higher percentage in circumstances with more headwind (Kretschmann et. al, 2015). New ship designs for autonomous vessels have eliminated the deckhouse structure, see Figure 27 for an example.

Figure 27: New Ship Design for an autonomous Vessels (Rolls-Royce)

By using the proportions and known estimated cross sectional area of the Panamax bulk carrier referenced in the MUNIN report, the same dimensions could be used to describe the design vessel's cross-sectional area, A_F. The details of this calculation were completed in MATLAB and attached in Appendix A.

The capital costs for a ship usually account for 42% of the total costs (Stopford, 2009) and consists of all expenses involved in purchasing a vessel, including the down payment received, financing cost and the building price of a new vessel (Kretschmann et al, 2015). Stopford mentions that ships financed with bank loans have a fixed cash flow which may exceed operating costs. Also, as a ship ages, its capital costs reduce, but voyage and operational costs increase. This is because newer vessels are more technologically efficient, a concept that may be applied for MASS.

Due to the concept of autonomous vessels being relatively new, not much price information is offered regarding the construction of this type of vessel. An estimation can be computed by using observed values associated with a similar ship type. The MUNIN Study's quantitative assessment mentioned that the new autonomous ship technology and safety systems implemented on board will indisputably increase the production costs. Moreover, if the machinery and propulsion constitute thirty percent of the total vessel production cost and there is an increase by one-third for additional costs associated with redundancy requirements, the total vessel cost will merely increase by ten percent (Kretschmann et al., 2015) compared to a traditional vessel of a similar type.

To approximate the capital cost associated with the bulk autonomous vessel, a consultation of the newbuild prices for a Handymax bulk carrier were referenced and the results are displayed in Figure 28.

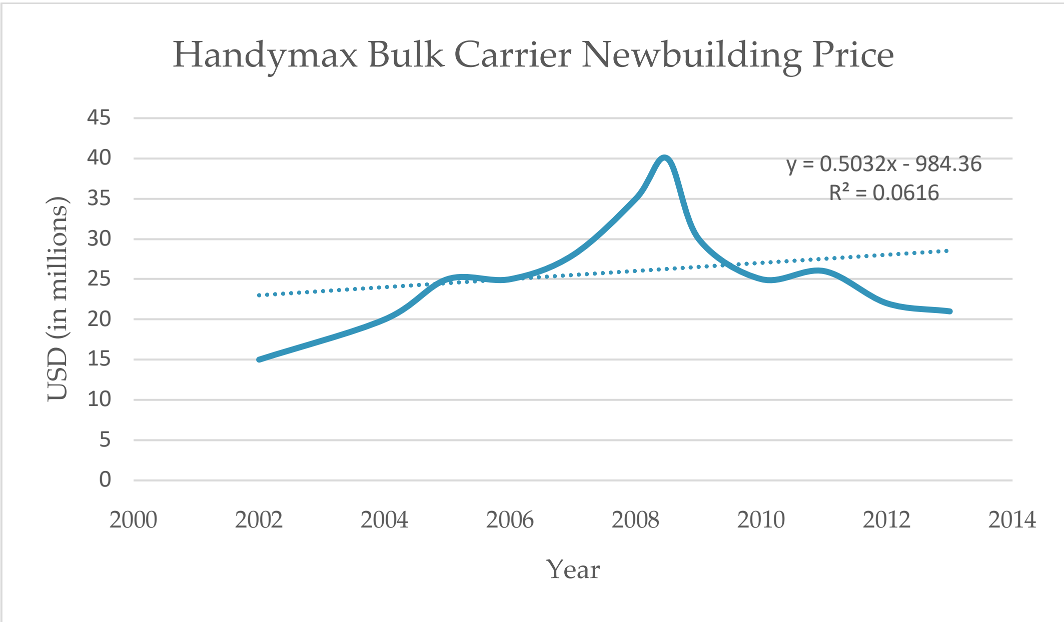

Figure 28: Handymax Bulk Carrier Newbuild Price (EquityGate, 2013).

The average price of a new vessel is USD 26.0 million, so the capital costs associated with a traditional bulk vessel for this study is assumed to be the same. Using the MUNIN report as a guide, the new building price for the autonomous vessel is 110 percent of the conventional bulk carrier price, so the price would be approximately USD 28.6 million. For this study, capital costs will be considered as just a one-time payment when a ship is ordered.

4.2

4.3 Environmental Sustainability

In this chapter, the environmental impact of shipping emissions is discussed. The first part of the chapter discusses the current ship emission trends and regulations. Later, the current Carbon Dioxide (CO_2) emissions information associated with the shipping sector is presented along with other predictions of emission growth. Then, the existing data on CO_2 emissions are used to estimate the future emissions in different scenarios: if no changes are made and potential improvements if autonomous vessels are implemented.

4.3.1 Present-day Ship Emissions

Although ocean transportation remains to be one of the most cost-effective, fuel-efficient and environmentally friendly methods to transport commodities, there has been a large focus recently on decarbonizing international shipping by 2035. It is worth noting that international shipping in this context is defined as "shipping between ports of different countries as opposed to *domestic shipping*… [excluding] military and fishing vessels" (IMO, 2009).

This would involve a gradual total reduction in greenhouse gas (GHG) emissions in international shipping. Almost all transportation GHG emissions are from the fossil fuel combustion of CO_2, but Methane (CH_4), Nitrous Oxide (N_2O) and Black Carbon (BC), a short-term pollutant, also play a role. In this study, the focus will only be on CO_2, the largest component of shipping GHGs, which is projected to rise in the shipping sector. Currently, maritime transport makes up about 2.6% of the total global carbon emissions with 938 tons of CO_2 emitted in 2012 (ITF, 2018). There are several drivers of emissions which include increased operating hours for many ship classes, more powerful main engines, growth in the size of the international fleet and large ship activity (ICCT, 2017).

There are a variety of strategies that can be implemented to improve the fuel efficiency of a vessel and decrease the overall emissions output. In terms of the overall vessel design, optimizing the hull design is a possibility, while operationally, ship speed reduction, voyage planning, and weather routing would be important cooperative measures (Crist, 2009).

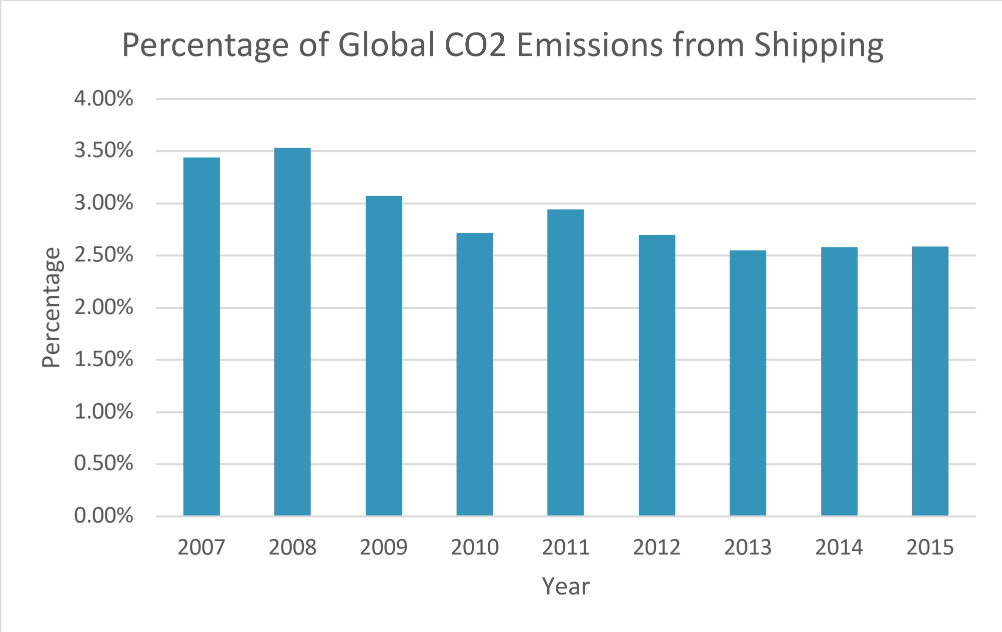

Figure 29: Total Shipping Percentage of Global CO2 Emissions

The IMO's mission is to promote safe, secure and efficient shipping with a vision to reduce GHG emissions from international shipping as soon as there are technologies developed regarding propulsion systems and new fuels (ICS, 2018). The IMO's Initial Strategy states a goal to reduce international shipping GHG emissions "by at least 50% by 2050 compared to 2008" (ITF, 2018) with an official study foreseeing an increase of 50-250% by 2050. The organization has the important duty of regulating the shipping sector and has implemented one directive for improving ship energy efficiency which entered into force 19 May 2005: the Energy Efficiency Design Index (EEDI) described in Chapter 4 of The International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI.

EDDI is a regulation that requires new ships to be at least 30% more energy efficient with their design and emission of CO_2 than ships constructed before 2013. This agreement is per unit of "transport work" or g CO_2 (generated) /dwt-nm or tonne mile (cargo carried). It also is a measure of the performance of a ship and hardware onboard. The EEDI requirement aims to increase the energy efficiency of new ships over time (IMO, 2018).

A simplified formula describing the EEDI is shown in Equation 8:

$$EEDI = \frac{\mathrm{P} * \mathrm{SFC} * \mathrm{C}_F}{\mathrm{DWT} * V_s}$$

Equation 8: Energy Efficiency Design Index (EEDI) (Tran, 2016).

where P is the engine power (kW); SFC is the specific fuel consumption (g/kW), which is the amount of fuel used for engines in an hour; C_F is the carbon factor or the amount of CO_2 generated per mass of fuel burned (g CO_2/g fuel); DWT is the dead weight tonnage or the ship capacity when carrying a full load and V_s the reference ship speed (nm/hour).

The IMO's Initial Strategy states a goal to reduce international shipping GHG emissions "by at least 50% by 2050 compared to 2008" (ITF, 2018) and in April 2018, IMO's Marine Environment Protection Committee (MEPC) adopted an "Initial Strategy" during the 72nd session called the "Initial IMO Strategy on reducing Greenhouse Gas emissions from ships". Many guiding principles for both the short, medium and long-term future and emission targets were established. The initial strategy is to be revised by 2023 (IMO, 2018). Although IMO has previously implemented mandatory measures to regulate GHGs internationally, with improving technological innovations and operational changes there is a further need to identify how other measures can be taken, like the use of alternative fuel or energy sources to accomplish the goal of zero-emissions.

The Organization for Economic Co-operation and Development (OECD) International Transport Forum (ITF) is an intergovernmental organization with 59-member countries, acting as a think tank for transport policy for all modes of transportation. The ITF is politically autonomous and administratively integrated with the OECD and published a case-specific policy analysis titled, "Decarbonizing Maritime Transport: Pathways to zero-carbon shipping by 2035" (ITF, 2018). A key reason that the goal year is 2035 is that there are existing technologies that have the ability to make the required improvements by that date.

The study examines what is required to decarbonize international shipping by 2035, including projections of future emissions created from baseline scenarios and recommendations on policies and measures to cut shipping emissions. If no actions are taken to limit carbon emissions today, there may be a projected increase by 23% or 1090 million tons by 2035 compared to 2015 (OECD 2018). Another forecast states that international shipping could become 17% of global CO_2 emissions in 2050 (ICCT, 2017).

There are many possibilities that can be used to decrease carbon emissions and improve the energy efficiency of vessels, including the use of alternative fuel sources or renewable energy, like hydrogen or electricity, improving the physical ship design eliminating bulky designs and heavier materials, or operational parameters such as reducing speeds typically associated with “slow steaming”. The largest impact is expected to be the use of alternative fuel sources, advanced biofuels and renewable energy in the coming years.

Technological advances could decrease the cost of many operational measures. For example, an ITF policy brief on the subject believes that a zero or low-carbon vessel will be more expensive than a conventional vessel during early development, but with increasing availability the costs will gradually decrease so that the ship becomes an affordable alternative for transporting commodities (ITF, 2018). It is worth noting, however, that shipping GHG emissions are on the rise despite these advances.

A visual representation of how carbon emissions could grow by 2035 are displayed in Figure 30. A further comparison can be completed against the real emissions in the year 2015 in Figure 31, showing a significant growth along the main East-West trade routes signifying a solution needs to be implemented to limit this outcome.

Figure 30: Visualization of CO2 emissions across global shipping routes in 2015 (ITF, 2018).

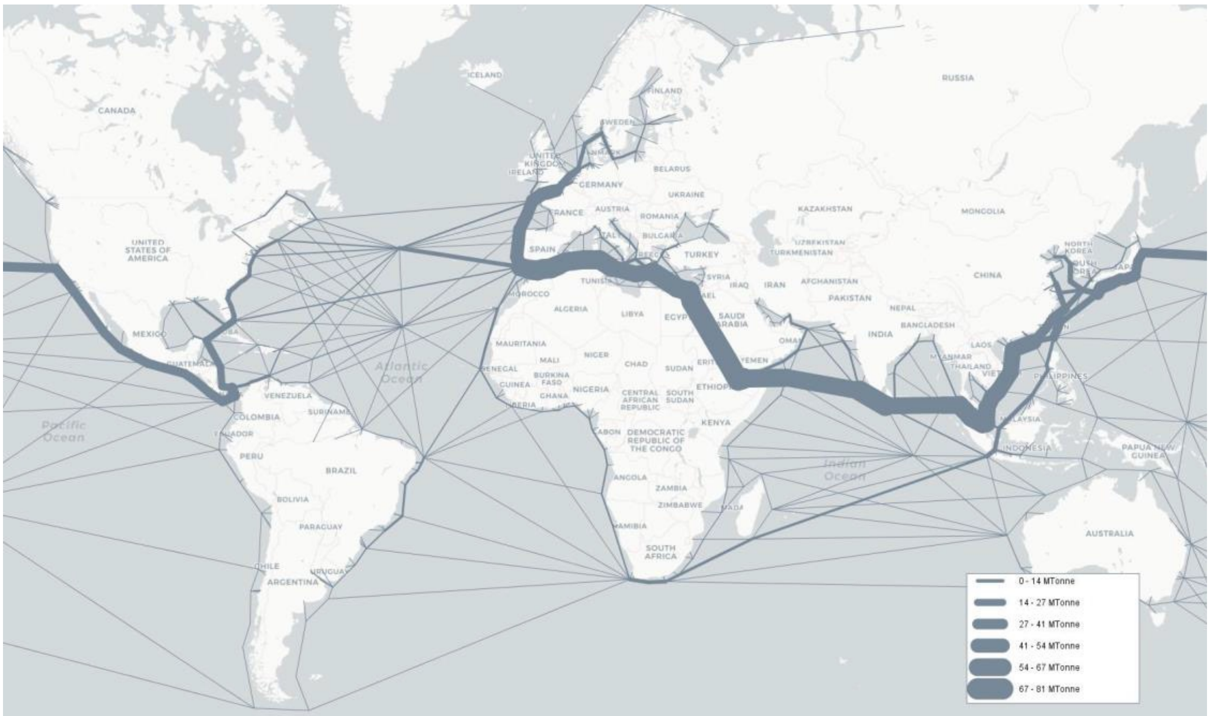

Figure 31: Visualization of CO2 emissions across global shipping routes in 2035 (ITF, 2018).

Also, a depiction of the distribution of CO_2 emissions from total shipping, including international, domestic and fishing, for 2015 are in the below figure. Both figures highlight the major shipping routes indicated by a higher emission concentration.

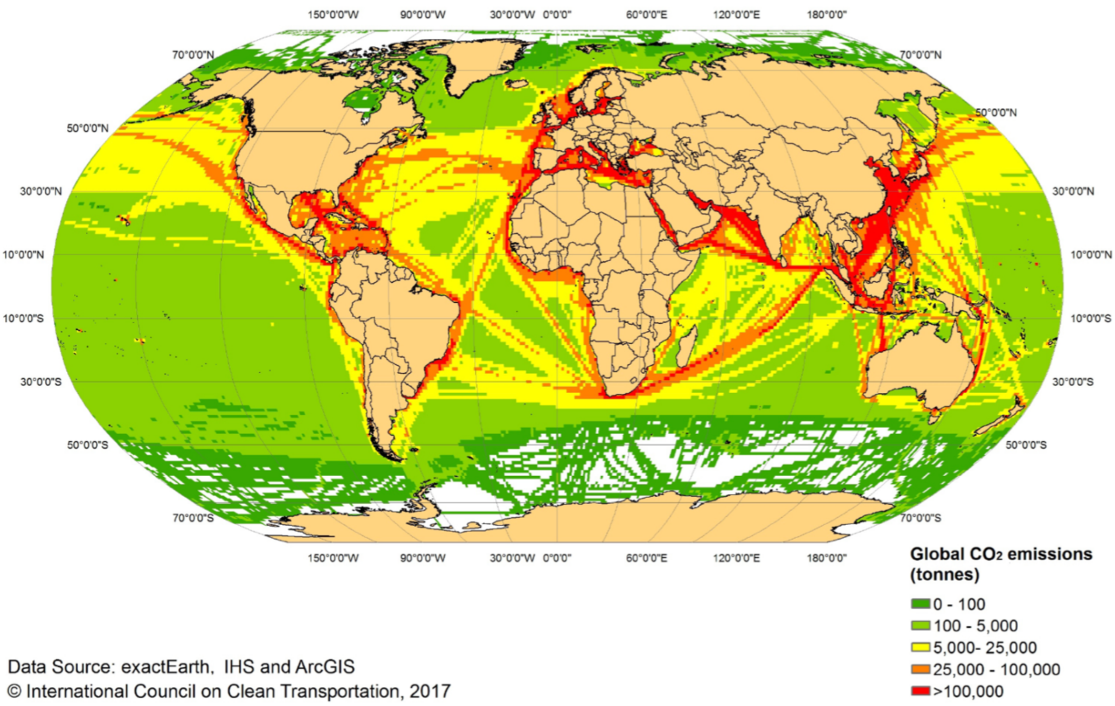

Figure 32: Global distribution of shipping CO2 emissions (ICCT, 2017).

To quantify the trend of shipping CO_2 emissions in recent years, data was gathered from the Third IMO Study between 2007-2012 (IMO, 2015) and ICCT between 2013-2015 (ICCT, 2017). The data is listed in Table 7and depicted in Figure 33.

Table 7: Shipping CO2 Emissions (million tonnes)

	2007	2008	2009	2010	2011	2012	2013	2014	2015
Global CO2 emissions	31959	32133	31822	33661	34726	34968	35672	36084	36062
International shipping	881	916	858	773	853	805	801	813	812
Total shipping	1100	1135	977	914	1021	942	910	930	932
% of global	3.4%	3.5%	3.1%	2.7%	2.9%	2.7%	2.6%	2.6%	2.6%

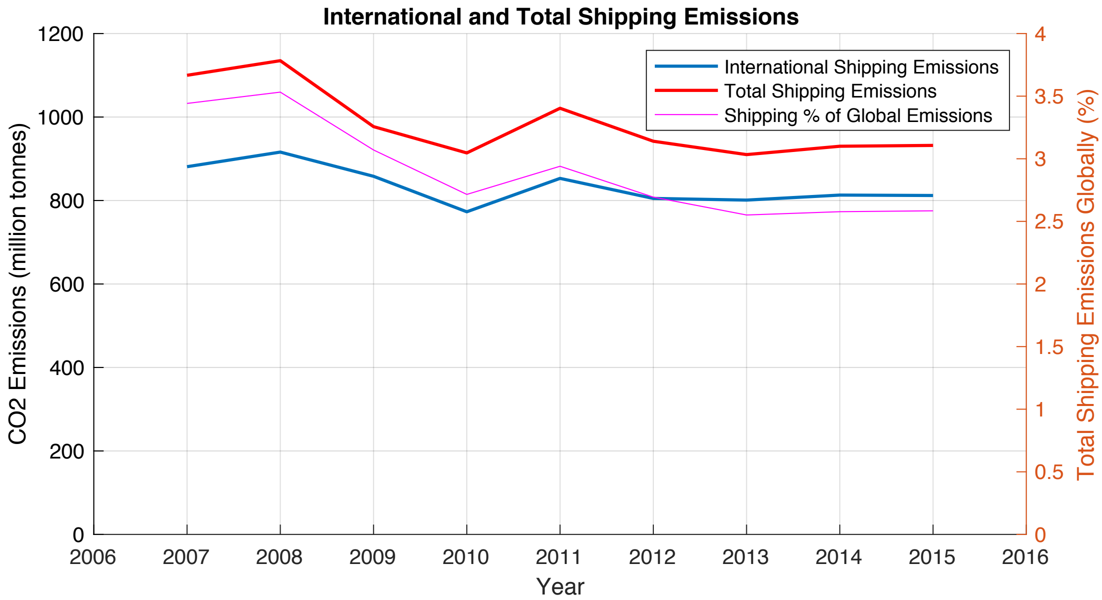

Figure 33: Shipping CO2 Emissions

From Figure 33, a conclusion can be made that total and international CO_2 shipping emissions have remained relatively constant between the years of 2013 and 2015. Using this data, total shipping emissions are shown to make up approximately 2.9% of the global CO_2 emissions, with international shipping comprising 2.5% of this percentage. The projected growth rate per year based on this data will be approximately 1.5% for global CO_2 emissions which corresponds to the growth rate in seaborne trade predicted by IMO (combined cargoes in terms of tonnage) of 1.5-3% annually (IMO, 2000).

Global shipping emissions are projected to grow at a rate of approximately 3% each year until 2050, signifying almost a double by 2035 (ITF, 2017). According to the International Council on Clean Transportation (ICCT), the total CO_2 emissions from international shipping were about 8% lower in 2015 than 2008, even though there was a 30% increase in maritime trade. Total shipping CO_2 emissions recorded increased by +2.4% from 910 to 932 million tonnes between 2013 and 2015, which made up approximately 2.5% of global emissions. 87% of these emissions can be attributed to international shipping.

A large contributor to the GHG growth is the increase in shipping fuel consumption in recent years. According to a 2015 study, the shipping fuel consumption has increased by 2.4% between the years of 2013 and 2015 from 291 million tonnes to 298 million tonnes (ICCT, 2017) in which there was a 1.4% growth attributed to international shipping. In Figure 24, the most widely used is identified as residual fuel with almost a quarter of the global shipping fleet using distillate fuel.

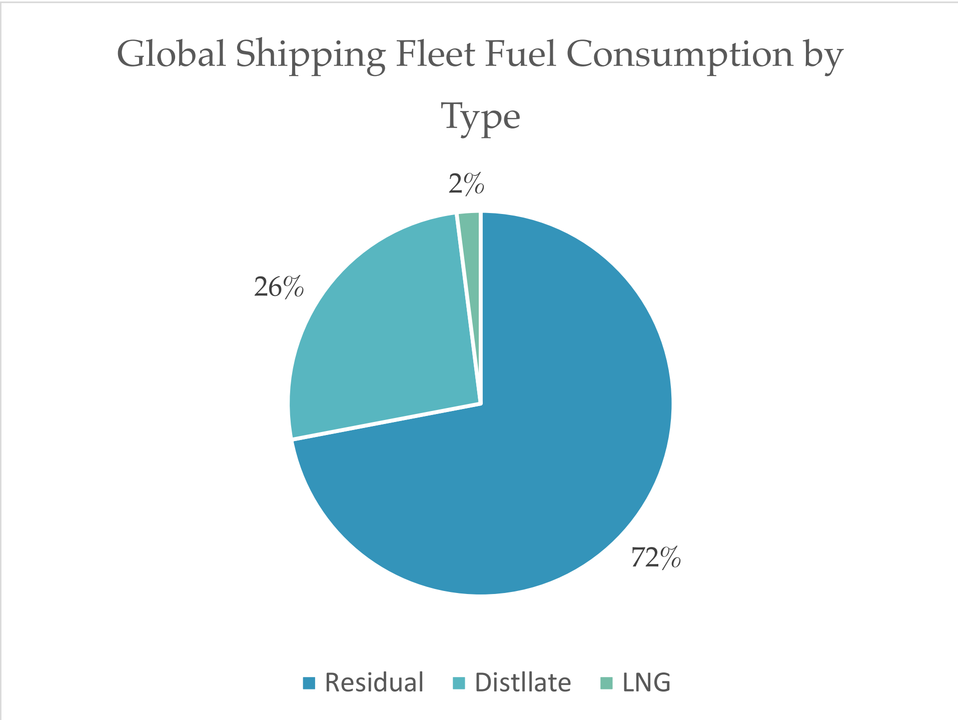

Figure 34: Fuel Consumption by the Global Shipping Fleet by Fuel Type (Adapted from ICCT, 2017).

According to the ICCT report on GHG emissions, there are three ship classes which account for the majority of CO_2 emissions, which include container ships at 23%, bulk carriers at 19% and oil tankers at 13%, while the other 45% is comprised of vessels from other classes. Most of these emissions occur when the vessel is cruising or waiting at anchor to berth, specifically with bulk carriers, tanker or general cargo vessels, for example.

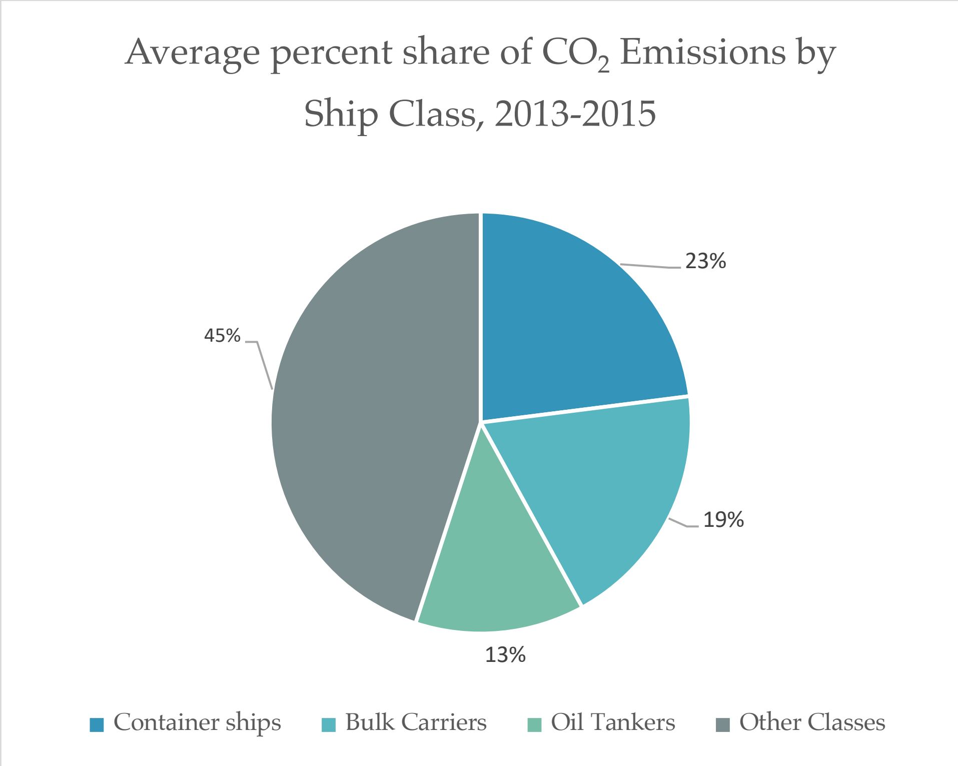

Figure 35: Average CO2 Emissions by Ship Class (Adapted from ICCT, 2017).

There are further developments that need to be considered including an updated version of the recent trends in ship emissions and the drivers in which policymakers should consider when making informed decisions, like transport demand, ship capacity and speed (ICCT, 2017). The fourth IMO GHG study will be initiated in 2019, with revisions to the strategy being adopted in 2023, while data regarding fuel oil consumption for ships over 5,000 gross tons will begin on 1 January 2019. Both advances will allow a current evaluation and prediction of the impact shipping emissions have had in the next few years and allow for a further improvement in energy efficiency involving the use of alternative fuel sources.

4.3.2 Environmental Revolutions with Autonomous Vessels

New developments in fuels and propulsion systems are taking the shipping industry by storm, some even being implemented on the first autonomous vessels. One trend to accomplish CO_2 reductions in the maritime sector is through the use of maritime batteries and carbon neutral fuels (Safety4Sea, 2018).

One existing example is through the use of electric propulsion which could be feasible for all ship types. Essentially the vessel would be powered by batteries, a development that has already taken place for ferries and offshore support vessels. The result is optimized efficiency and reduced fuel consumption (ICS, 2018).

Currently, this zero-carbon method is only implemented on short voyages and to implement this propulsion method on a large scale, an infrastructure overhaul will need to take place to ensure that electricity is accessible at all ports.

This is just one of the first steps necessary in accomplishing the goal of decreasing emissions in the shipping sector. Hydrogen and fuel cells are also being considered for longer journeys. Nevertheless, there needs to be more research into zero CO_2 emission fuels "that are both environmentally sustainable and economically viable" (ICS, 2018).

4.4 Performance Assessment Methods

In this section, an evaluation of potential freight costs for an autonomous vessel is computed. Autonomous vessels are predicted to have another improved economic benefit, a 3.4% reduction in the cost of carrying freight (Kretschmann et. al, 2017) compared to a traditional vessel.

4.4.1 Freight Costs

A simple way to measure transportation performance is by multiplying the total cargo weight by the distance the cargo will travel, and then dividing by the cost, as shown in the below Equation 9:

$$x = \frac{\mathrm{d} * \mathrm{w}}{\mathrm{c}} = \frac{distance * weight}{cost}$$

Equation 9: Transportation Performance (Adapted from L. Benson et. al, 2018).

It is forecasted the global trade will expand by 2.4% (WTO, 2017), so if we assume there is a technological improvement rate at the same pace for ocean transportation, a future prediction of performance can be estimated. In addition, probability distributions can be used to foresee outcomes regarding transportation performance, specifically in terms of costs.

For our case study in Section 6 , an estimation of the Maritime Transport Costs (OECD, 2010) from the United States (exporter) to Yemen (importer) are needed, which are displayed in three different measures in Table 8:

Table 8: Transport Cost Measure definition

Transport cost measures	**Variable**	**Description**
Transport cost	(tr_cost)	expressed in USD
Unit transport cost	(tr_unit)	transport cost per kilogramme; the cost in USD required to transport one kilogramme of merchandise
Ad valorem equivalent	(tr_adva)	transport cost divided by the import value; the share of transport cost represents in the total import value of the produce

5 Results & Data Analysis

5.1 Costs

In this section, the costs will be calculated as input for the shipping cash flow model.

5.1.1 Operating Costs

The economies of scale graph for bulk shipping is used as a reference for the Shipping Cost Model. For example, if we reference Figure 36 below and look at the dwt of our design vessel (45,500 dwt), we can get an estimate for the annual costs associated with the vessel. By using an average inflation rate of 2.15% per year, we are able to compute the annual projected cost of a bulk carrier in 2019.

Table 9: Projected Operating, Voyage and Capital Costs from the Economies of Scale Graph

Average rate of inflation =	2.15%	per year
Calculating Present Value (PV)	1997	2019
Operating Costs	$1,500,000.00	$2,395,164.91
Voyage and Capital Costs	$800,000.00	$1,277,421.28
Fuel Costs	-	-
Total Costs	$2,300,000.00	$3,672,586.19

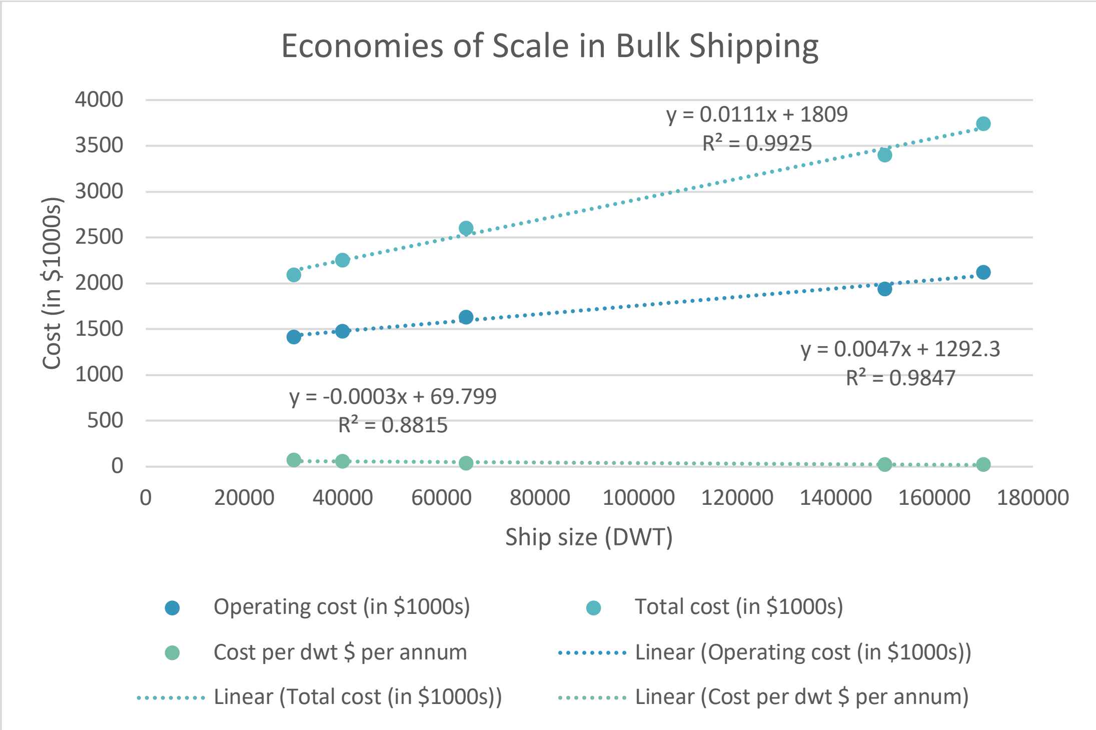

Figure 36: Economies of Scale in Bulk Shipping (Stopford, 1997).

5.1.2 Voyage Costs

In this section, the voyage costs associate with the fuel and the total hull resistance (i.e. air resistance) will be estimated.

5.1.2.1 Fuel Costs

By using the existing prices recorded between early 2016 and 2019, the average price per metric ton calculated for IFO 80 was $364.32 and MGO was $535.27. The FORECAST function in Microsoft Excel was utilized to estimate the future price of MGO, the fuel type used for our analysis. The calculations behind the function are shown in Equation 10 and Equation 11 and the results are shown in Figure 28 and 29 below:

$$a = \bar{y} + b\bar{x}$$

Equation 10: Excel Forecast Function - Equation 1

and

$$b = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sum(x - \bar{x})^2}$$

Equation 11: Excel Forecast Function - Equation 2

where x and y are the sample means.

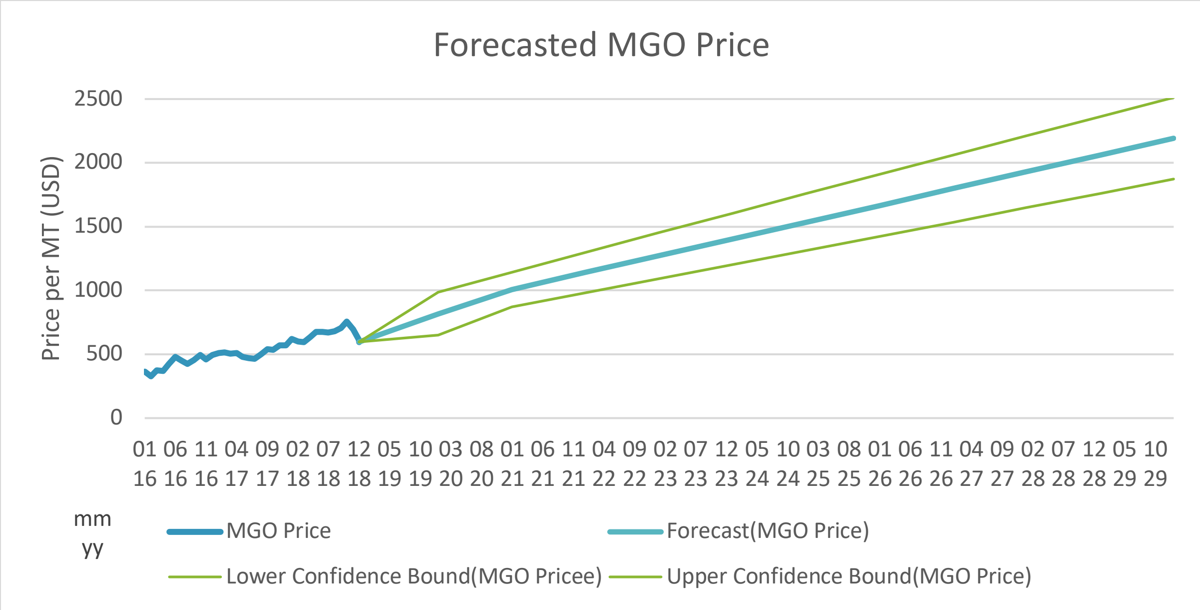

Figure 37: Forecasted Price of MGO from the FORECAST function

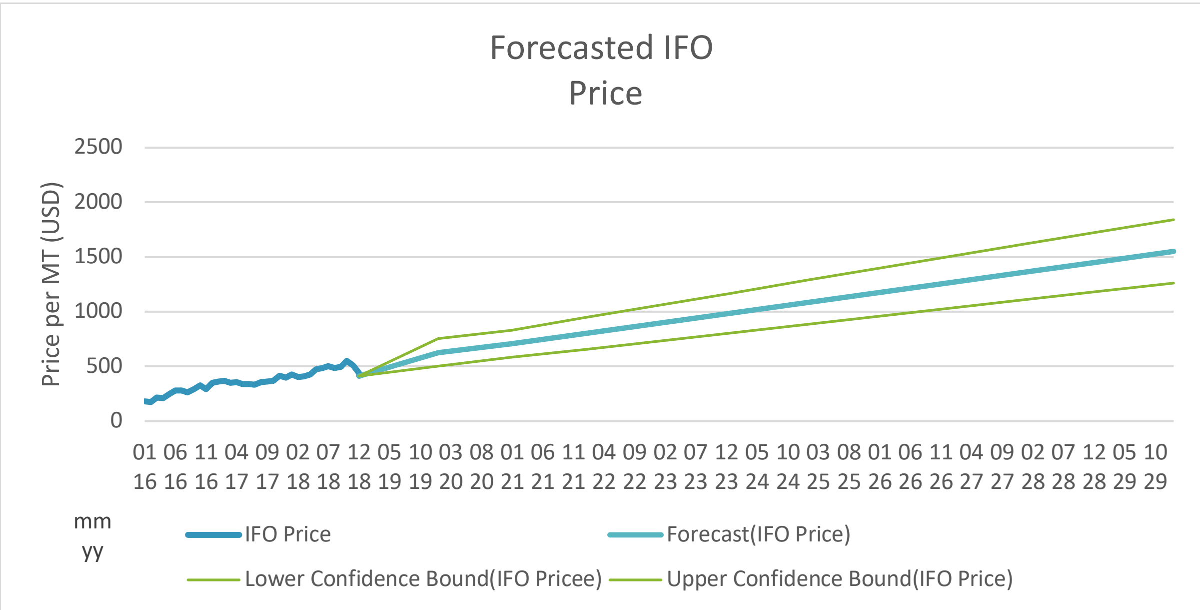

Figure 38: Figure 15: Forecasted Price of IFO from the FORECAST function

This forecast only holds true if the fleet size and fuel consumption remain the same and the growth in bunker pricing trends continue steadily as predicted in the graph. For simplicity, the fuel cost will be determined by using reasonable prices of the IFO and MGO price associated with the design vessel characteristics detailed in Table 10.

Table 10: Median Fuel Price Estimate

	Median Price in USD per MT
MGO	1,091
IFO	732

5.1.2.1 Total Hull Resistance (Air Resistance)

The total hull resistance is simplified in this report as only the air resistance. First, a computation of the approximate cross-sectional area of the Handymax bulk carrier vessel in both the ballast and design conditions is shown in Figure 39.

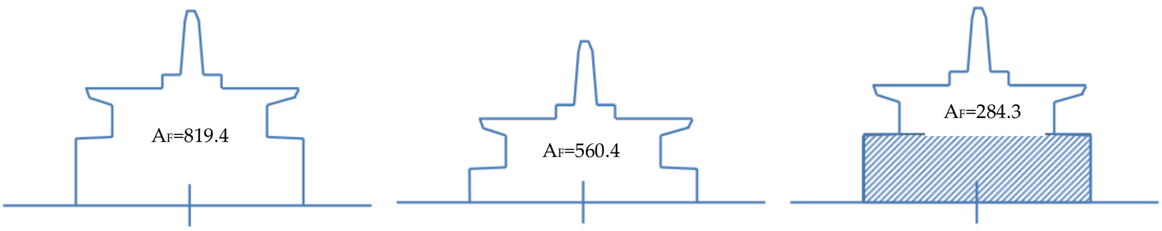

Figure 39: Wind frontal area in the ballast and design conditions (Adapted from Kretschmann et. al, 2015)

The autonomous vessel would experience only approximately 66% of the air resistance force that a traditional vessel experiences in both the ballast and design conditions, suggesting that fuel efficiency would be improved for MASS with this decrease in resistance force.

Table 11: Cross sectional area and air resistance in diverse conditions

Condition Description	Cross sectional area (m^2)	Air resistance (kN)	
		Traditional	Autonomous
Ballast	819.4	23.1	15.3
Design	560.4	15.8	10.5
Deckhouse	284.3	8.0	5.3

Using the same values for the coefficients ϱ, the air density and C_d is the wind resistance coefficient (0.45 for autonomous and 0.68 for traditional vessels), the relationship between the speed (in knots) and the hull resistance force associated with air resistance is depicted in Figure 40. At higher vessel speeds, more opposing forces act on a vessel and the effects are higher for a traditional vessel than an autonomous. At 15 knots in the ballast condition, there is a decrease in resistance forces of approximately 33.8% for the autonomous condition.

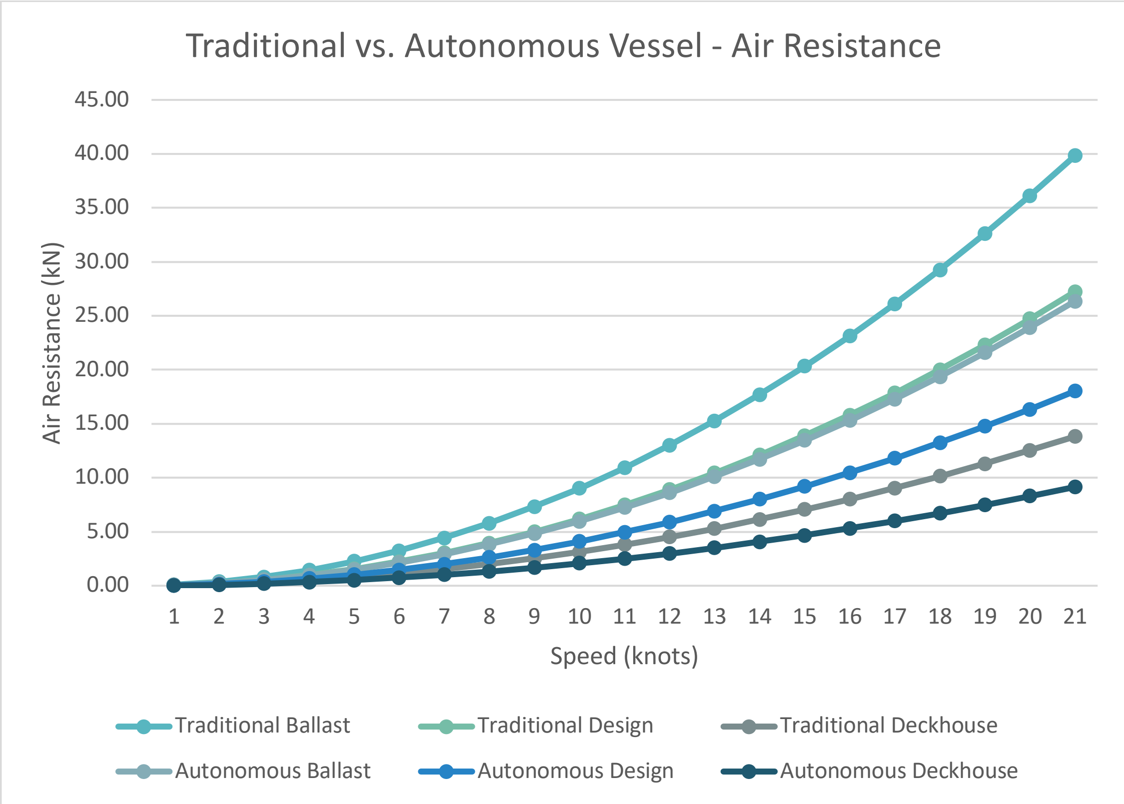

Figure 40: Total Hull Resistance Forces Associated with Air Resistance

Furthermore, an estimation of the propulsion power reduction can be computed using the equation for EHP, with the velocity equal to 15 knots (7.717 m/s or 25.32 ft/s). Only the air resistance is considered in the computation for amounts in Table 12.

Table 12: Reduction of horsepower due to lower air resistance

Condition Description	Propulsion Power needed for Air Resistance Force (kW)		Propulsion Power Reduction (kW)
	Traditional	Autonomous	
Ballast	178.4	118.1	60.3
Design	122.0	80.8	41.3
Deckhouse	61.9	41.0	20.9

When comparing the traditional and autonomous vessels propulsion power required to counteract the air resistance force, there is a reduction of approximately 34% for the autonomous vessel. This signifies that there is less overall hull resistance with the new technological ship design, as confirmed previously. This concept matches the MUNIN study's idea that the propulsion power will reduce by about 1% at the design speed (Kretschmann et. al, 2015).

The same relationship is shown in Figure 41 which relates the ship's speed (in knots) to the effective propulsion power required. At higher speeds, there is more propulsion power needed from the engines to overcome the resistance forces.

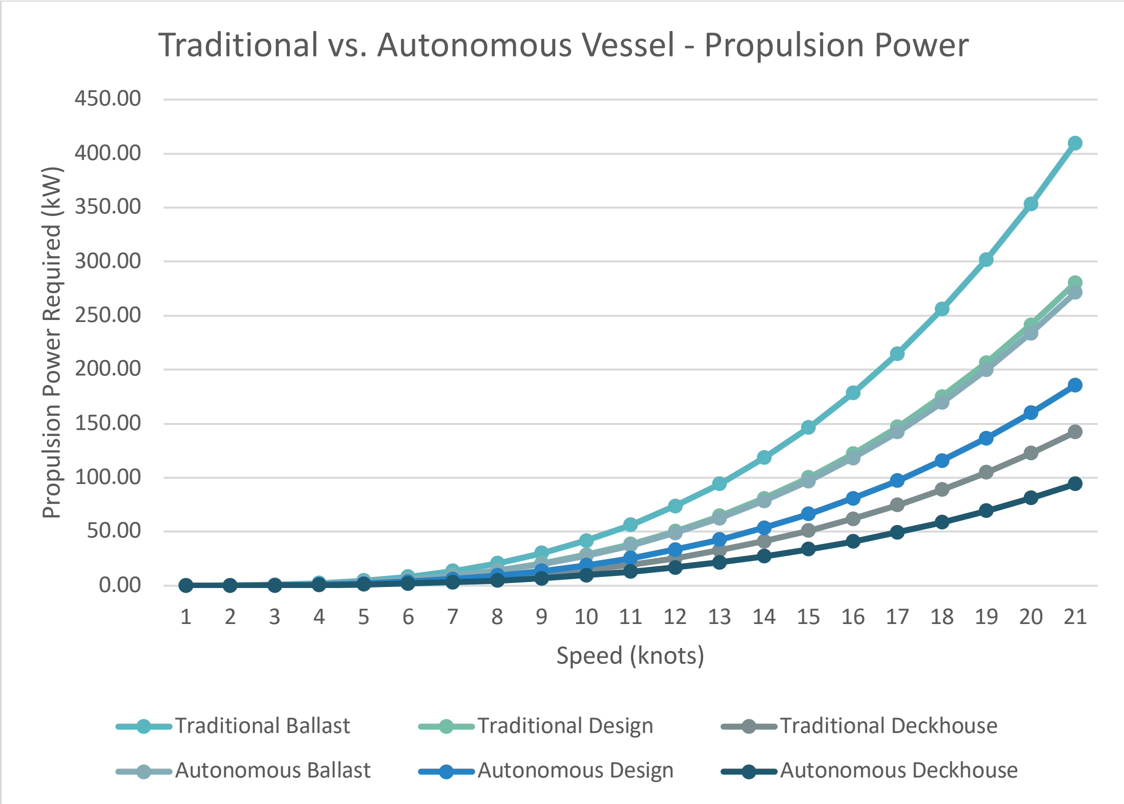

Figure 41: Total Propulsion Power Associated with Air Resistance

For simplicity, there will be an associated reduction in fuel consumption of about 1% as well, since the effects of implementing an autonomous vessel are assumed to be proportional to the propulsion power. There are other factors not included in this study that impact the overall resistance felt by a vessel such as steering resistance, current resistance, wave resistance, and shallow water resistance.

5.2 Environmental Sustainability

5.2.1 Forecasting ship emissions

Projecting ship emissions is vital to comprehend and measure the effects of climate change. The third IMO GHG Study published in 2014 utilized two different approaches for estimating ship emissions: the top-down and bottom-up approach.

The top-down evaluation uses bulker sales from the International Energy Agency (IEA) to calculate CO_2 emissions, but is less precise due to "specific types of error in energy data that involve marine bunkers" (IMO, 2018). The bottom-up approach is more accurate and merges the Automatic Identification System (AIS) system with data from the IHS Fairplay global fleet data. The outcome included statistics on energy use, activity and emissions for all ships between the years of 2007 and 2012. Figure 42shows the fuel consumption estimates from the sources mentioned previously.

The top-down estimates from IEA are always lower than the Third IMO GHG Study and ICCT fuel consumption estimates. This is most likely due to how domestic and international shipping are defined. IEA considers international shipping a vessel which sails between two ports in two different countries, while ICCT assumes that the size of a vessel indicates its position in an international shipping role (i.e. a larger vessel will travel international), which is not always the case.

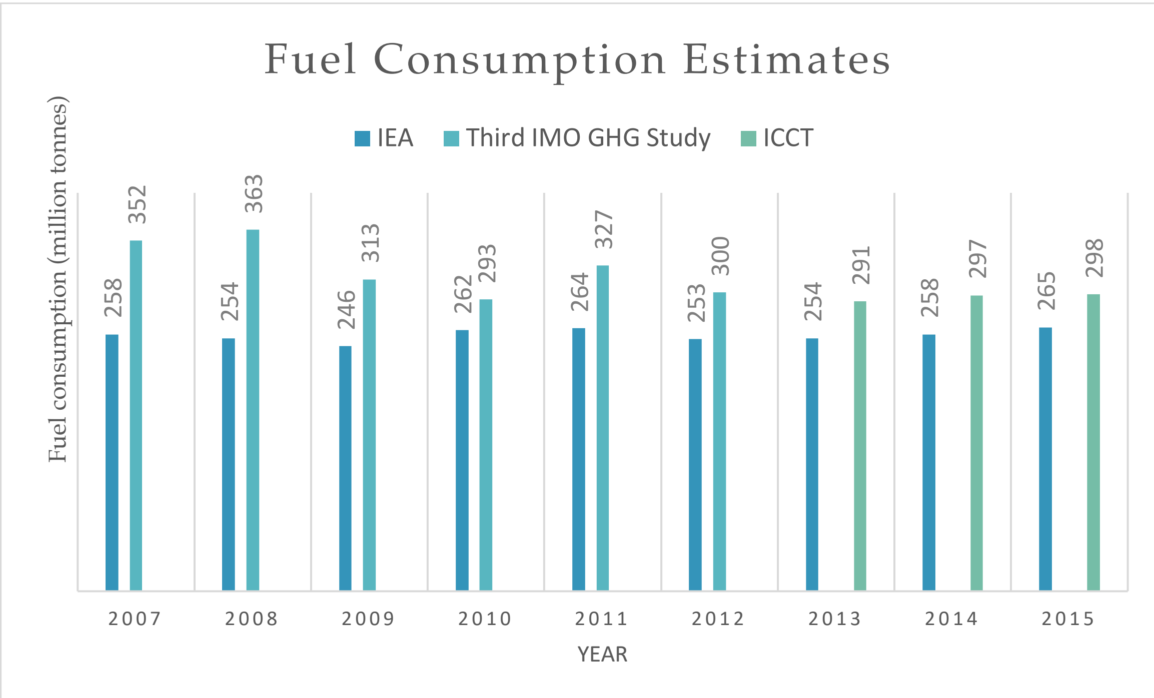

Figure 42: Fuel Consumption Estimates from IEA, IMO, ICCT, 2007-2015 (Adapted from ICCT, 2017).

There are also two other approaches that can be applied. Both use an extrapolation of the existing emissions data, the fleet numbers and the fleet powers to estimate future ship emissions (Endresen, et. Al, 2008).

The different ways to forecast future ship emissions are shown in Figure 43:

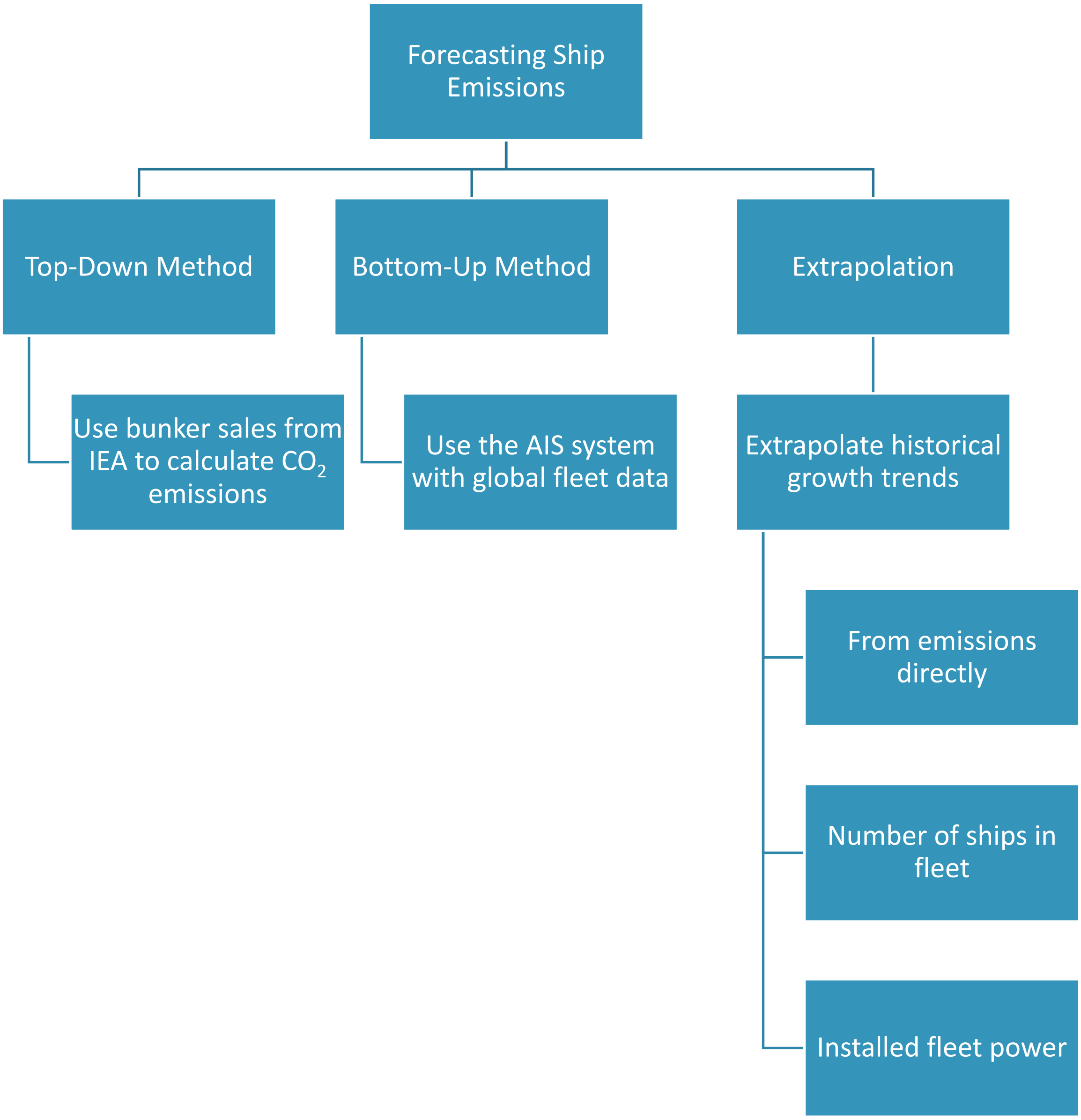

Figure 43: Emission Estimation Flow Chart

For this thesis and simplicity's sake, the extrapolation of historical growth trends, specifically from emissions directly and the number of ships in the fleet will be used for our analysis.

5.2.1.1 *Data extrapolation*

5.2.1.1.1 Historic Growth Trends using Emissions

An extrapolation of the historical growth trends from Table 7 was completed to estimate future vessel emissions. If we considering no technological advances or other alternative fuel source use a simplified projection of Shipping CO_2 emissions would follow the pattern in Figure 44. This is of course a simplified evaluation of the potential impact that the CO_2 emissions could have on the global climate if the growth in the global CO_2 emissions continues as is. This trend is presented below:

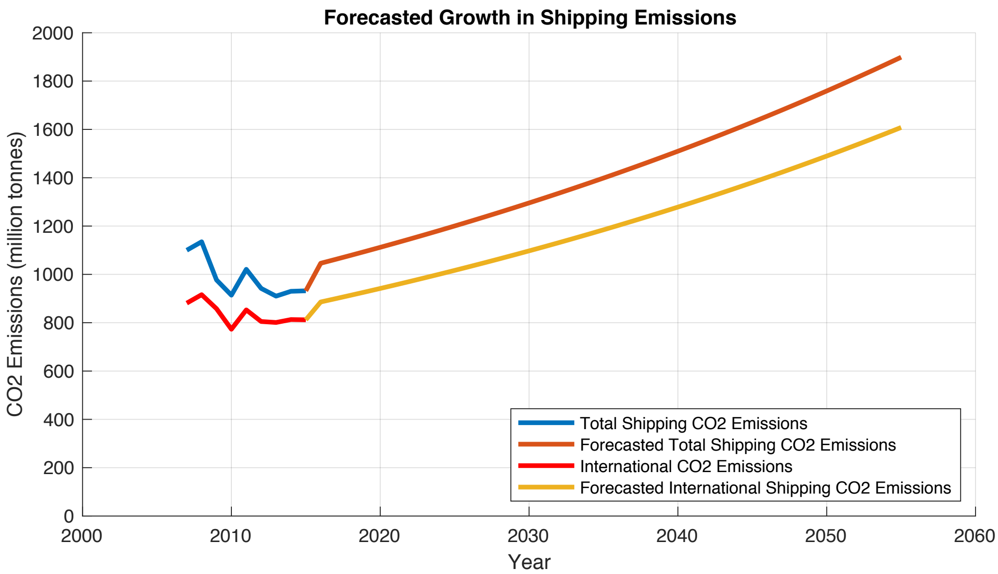

Figure 44: Simplified Projection of Shipping CO2 emissions

An IEA technology brief 2004d (Kahn et. al, 2007) examined scenarios for mitigating global transportation CO_2 emissions and mentioned five short-term measures that could be implemented including improvements in the fuel economy of gasoline and diesel, hybrid vehicle growth, a widespread introduction of biofuels and a reduction of travel demand.

In Table 13, the carbon emission savings are referenced with percentages. These values will be used to approximate different emission scenarios to show how autonomous vessel usage could decrease emissions in the shipping sector. The following mitigation measures will be applied:

Table 13: Summary table of Mitigation Policies

Technology	Carbon reduced/vehicle (%)
Diesels	18%
Hybridization	30%
Biofuels	20-80%
Fuel cells with fossil hydrogen	45%
Carbon-neutral hydrogen	100%

By improving the world fuel economy, there is a projected reduction in CO_2 emissions of 18 percent by 2030. With the use of biofuels and fuel cells with hydrogen refueling, there is an improvement of 12 percent and 7 percent, respectively in the same time frame. If all three of these methods are utilized, there is a potential to reduce CO_2 emissions by 30 percent.

Using the average global emissions growth rate of 1.48% observed in Table 14 and the average shipping emissions percentage of the global CO_2 emissions 2.9%, an estimated value for the total shipping emissions can be made for 2016 through 2019.

Table 14: Projected Emissions between 2016 and 2019 for Light-Duty Vehicles

Year	2016	2017	2018	2019
Global CO_2 emissions (in million tonnes)	36595.8	37137.4	37687.1	38244.9
Total shipping CO_2 Emissions (in million tonnes)	1061.5	1077.3	1093.2	1109.4

If an assumption is made that the total shipping emissions reach their maximum in 2019 and begin to decrease according to the mitigation measures mentioned, the results would be as follows:

Table 15: Projected Emissions with Mitigation Measures

	Current	No changes	Improving fuel economy	Biofuels	Fuel cells	All 3
Year	2019	2030	2030	2030	2030	2030
Percentage Change	-	0%	-18%	-12%	-7%	-0.3
Global CO2 emissions (in million tonnes)	38244.9	44953.4	36861.8	39559.0	41806.7	31467.4
Total shipping (in million tonnes)	1109.4	1304.0	1069.3	1147.5	1212.7	912.8

With the implementation of new technology and alternative fuels, MASS has the ability to slow down environmental emissions in the shipping sector. Although this was just a preliminary analysis of the potential changes in CO_2 emissions that are possible with various mitigation measures, it serves as a foundation to evaluate which measures have the most impact. If no changes are made, by 2030 the estimated total shipping emissions will grow to a new record of approximately 1,304 million tonnes, which is an increase of 17.5%. The most efficient single mitigation measure would be to improve the global fuel economy which is the relationship between the distance a vessel travels and the fuel consumed.

5.2.1.2 Shipping Emissions Algorithm

Another procedure to estimate shipping emissions is to set up a decision-making aid and policy evaluation tool (Kontovas et. al, 2009) which can be used by ship owners who need to calculate bunker consumption and exhaust emissions. There is assumed to be the following ship route:

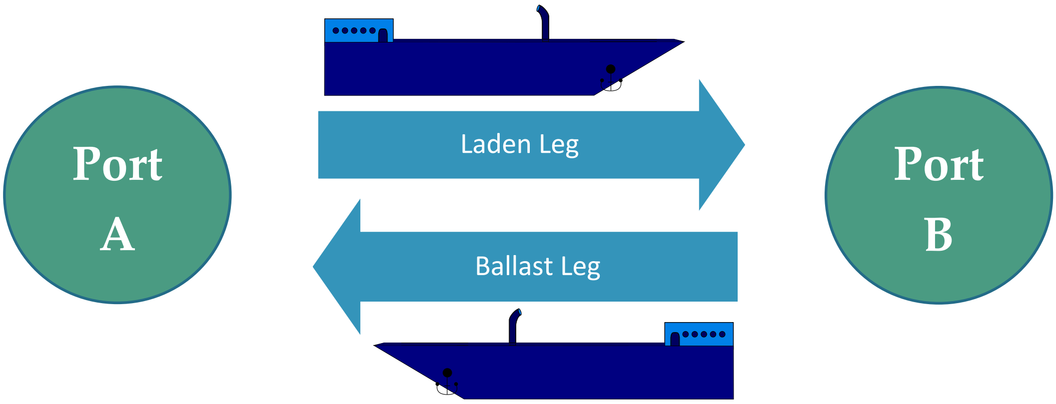

Figure 45: Ship Route Design Algorithm

For the model, a ship carries a cargo payload W (in metric tonnes) from Port A to Port B a designated distance apart L (in kilometers). The ship wil speed T (days) loading in Port A and time t (days) discharging at Port B. The vessel will go laden from A to B at a speed V (km/day) and return empty on ballast at speed v (km/day). The cargo payload, W depends on the ship's characteristics (i.e. deadweight, capacity utilization, etc.) Additionally, the fuel consumptions (in tonnes/day) are assumed to be known at the loading port, G; at sea when laden, F; at the discharging port, g; and at sea on ballast, f.

From Stopford (1997), a Panamax bulk carrier has a main engine consumption of approximately 35 tons per day when traveling at 15 knots. This will be used as an assumption for the fuel consumptions that are input into the MATLAB model at the loading and discharging ports. The same will rate will be applied when traveling laden and ballast on the sea voyage.

Table 16: Speed and Fuel Consumption Relationship for a Panamax Bulk Carrier (adapted from Stopford, 1997)

Speed (knots)	Main engine fuel consumption (tons/day)
11	14
12	19
13	24
14	30
15	36
16	44

The output of the algorithm is the total CO_2 emissions produced per round-trip shown in Equation 12 and per tonne-km in Equation 13.

$$EM_{TOT} = EF(GT + F\left(\frac{L}{V}\right) + gt + f\left(\frac{L}{V}\right)$$

Equation 12: Total Emissions Produced in a Round-trip Journey

$$EM_{TKM} = \frac{EF\left(\left(\frac{GT + gt}{L}\right) + \left(\frac{F}{V}\right) + \left(\frac{f}{v}\right)\right)}{W}$$

Equation 13: Total Emissions Produced in a Round-Trip Journey per tonne-km

Where EF is an emission factor of 3.17, an empirical mean used to compute CO_2 emissions which is based on fuel consumption. It does not depend on the fuel or engine type used.

The parameters for the design vessel will be implemented into the algorithm in MATLAB as shown in Appendix A for the following Case Study in Section 6.

5.3 Shipping Cost Model Analysis

In this section of the report, different scenarios will be presented to predict how autonomous vessel use can alter the voyage, operational and capital costs. The yearly assumed operational profile for the traditional and autonomous vessel are shown in Table 17and the vessel's lifetime is set to 25 years for the analysis.

5.3.1 Base Scenario Results

The base case scenario estimates the current bulk vessel operating costs for 45,000 DWT Handymax traditional vessel. The costs and percentages associated with each are adapted from the Capesize bulk carrier vessel in Figure 23 and the operational profile shown in Table 17 was based on the economies of scale table presented in the same section. To describe the present value of the costs referenced in the Stopford report, the average inflation rate per year of 2.15% was utilized to bring the costs to present day.

Table 17: Assumed Yearly Operational Profile

State	Days
Ship at sea	270
Ship at berth/waiting	95

To further analyze the effects of autonomous vessels on the total voyage, operational and capital costs the Kretschmann et. al (2015)'s comparison can be used as a guide. For the autonomous vessel operation, there is an assumption that the SCC handles 24 vessel operations per year. Also, voyage costs are neglected as they are variable with each journey:

Table 18: Total Costs of Traditional and Autonomous

	Traditional	Autonomous
Operating Cost	**$ 2,294,882.00**	**$ 2,663,061.00**
Crew cost (20 people)	$ 735,840.00	$ (945,000.00)
Stores & consumables	$ 288,836.00	$ (44,000.00)
Regular Maintenance & repair	$ 268,151.00	$ 135,281.00
Insurance	$ 312,780.00	$ 312,780.00
General Cost (SCC)	$ 269,275.00	$ 2,784,000.00
Periodic Maintenance & Repair	$ 420,000.00	$ 420,000.00
Voyage Cost	**-**	-
Fuel Price	-	-
Port Call Cost	-	-
Capital Cost	**$ 34,000,000.00**	**$ 37,400,000.00**
One-time payment	$ 34,000,000.00	$ 34,000,000.00
Total costs per year (excluding Capital and Voyage Costs)	**$ 2,294,882.00**	**$ 2,663,061.00**

With autonomous implementation, the largest decrease involves the operating costs associated with the crew cost. This will decrease by an estimated 228% per year, but the overall operating costs for an autonomous vessel is still estimated to be 16% higher than a traditional vessel. Also, with the need for a SCC autonomous vessel have a larger investment cost. The periodic maintenance and repair are assumed to be equivalent, but the new build autonomous vessel will be 110% of the conventional bulk carrier due to its technological advantages. In conclusion, autonomous vessels may result in savings over the 25 year lifetime of the vessel as crew and initial investment costs decrease.

6 Case Study: Autonomous Vessel

The emissions model discussed in Section 3.2 will be applied to a specific case study involving a bulk carrier vessel transporting goods from Houston, Texas to Aden, Yemen.

6.1 Design Vessel

WFP frequently ships many commodities in bulk, like lentils, peas, wheat flour, wheat and beans, so having a design vessel matching the proper handling characteristics is essential. Handymax is a type of medium size bulk carrier which is one of the most popular in the dry bulk market and can transport a variety of cargo types in its holds. This is advantageous because the model is flexibility to handle various cargoes and is geared which allows it to operate in ports without existing facilities or shore equipment, an essential aspect in some of the ports in which WFP operates. The freight weight associated with the shipment is 25,000 MT of wheat and the design vessel will sail at 15 knots when laden (loaded) and when returning empty on ballast. From dry bulk vessel port surveys, the ship time spent loading at Port A and B was determined to be approximately 1 day. The characteristics of the design vessel are summarized in Table 19:

Table 19: Design Vessel Characteristics

Length over all (m)	189.99
Length between perpendiculars (m)	182.00
Breadth (m)	32.24
Depth (m)	17.00
Draft (m)	11.00
Deadweight (t)	45500.00
Main engine (kW)	8580.00
Auxilary Engine (kW)	3 x 680.00
Trial speed at design draft (kn)	15
Cargo holds	5
Cranes	4
Crane lifting capacity (t)	35

6.2 Design Route

The design route, shown in Figure 46, will be from the Port of Houston in the United States to the Port of Aden in Yemen. The hypothetical plan is for the vessel to load in Houston, pass through the Gibraltar Strait connecting the Atlantic Ocean and Mediterranean Sea, the Suez Canal in Egypt, the Red Sea and the Gulf of Aden before discharging.

The total estimated route distance is 8,124 nautical miles (15045 km) and when traveling at a speed of 15 knots, the total trip will be approximately 23 days, not considering weather or other unforeseen delays.

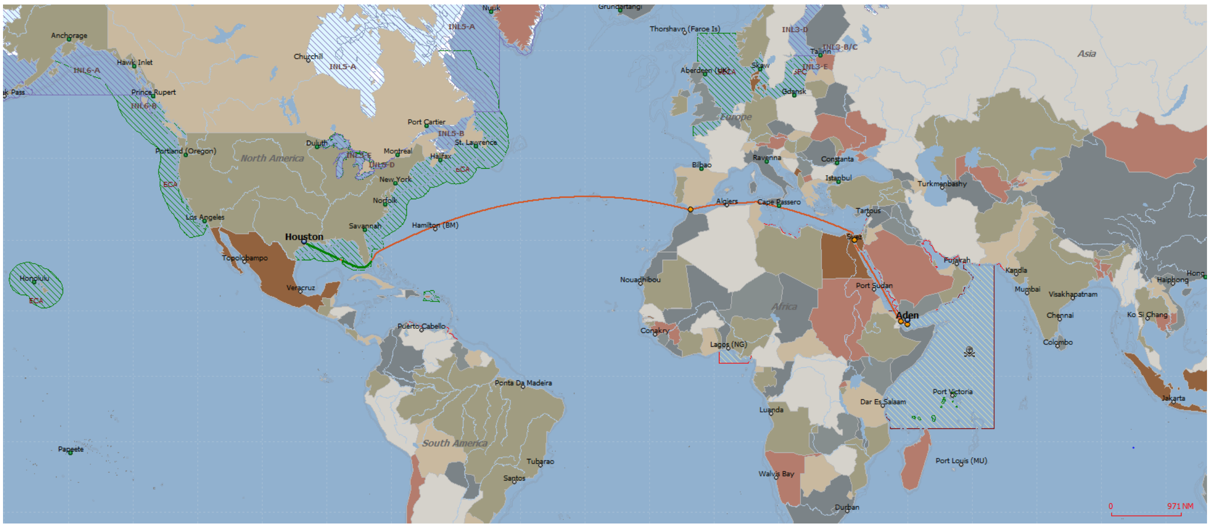

Figure 46: Design Route (Netpas Distance 3.4).

To get a better idea of the normal shipping routes traveled, a figure showing the most dense areas is shown below:

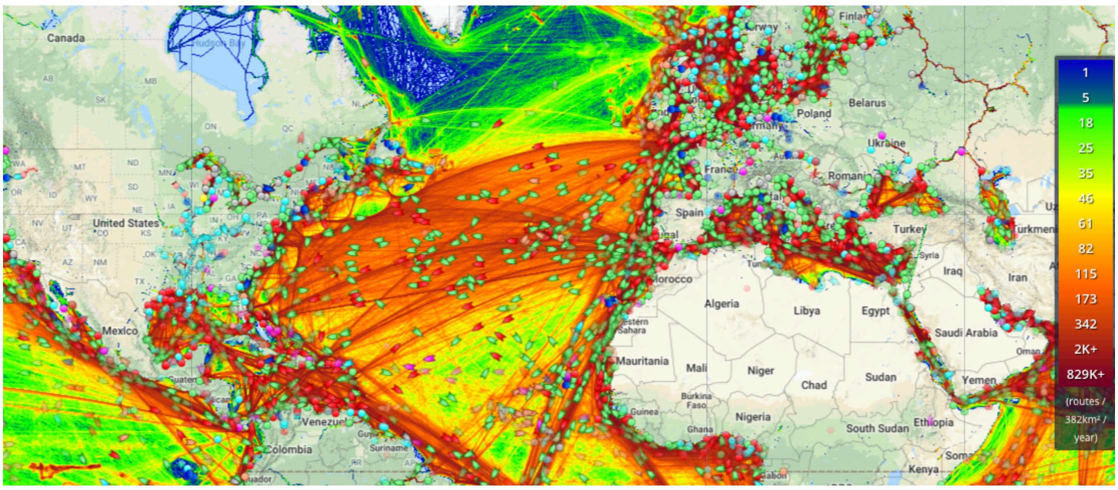

Figure 47: Marine Traffic Density Map (MarineTraffic, 2017).

6.3 Environmental Assessment

6.3.1 Trip Emissions

Continuing with the shipping emissions algorithm discussed in Section 3.2, the input variables will be as follows:

Table 20: Traditional Design Vessel Input Variables

Variable	Value	Unit
W	25000	MT
L	8124	nm
V	15	kn
v	15	kn

If we assume that there are zero MT registered during the ballast leg of the trip, and that the average cargo capacity of the vessel is 0.5, signifying the ship travels with a full load in one direction and empty on ballast, the results are as follows:

Table 21: Results of Algorithm for Traditional Design Vessel

Transit time from A to B	22.6	days
Distance between Port A and B	15045.6	km
Ship speed when going laden/ballast	666.8	km/day
Ship time speed loading/discharging at Ports	1.0	days
Ship operational days per year	270.0	days
Total fuel consumption per day (all states)	36.0	tonnes/day
Total fuel consumption at sea per round-trip	1624.7	tonnes
Total fuel consumption per round-trip	1695.2	tonnes
Total carbon dioxide produced per round-trip	5373.9	tonne-km
Total tonne-km's carried per round-trip	376141200.0	tonne-km

The same analysis was applied to an autonomous vessel with the same design characteristics, but used the assumption that the "fuel consumption is 25% less" (Futurenautics, 2016) or 27 tonnes/day instead of 36 tonnes per day for all phases of the journey. The results are as follows:

Table 22: Comparison of Traditional and Autonomous Vessel Emissions

	Traditional	Autonomous
Total fuel consumption per round-trip (tonnes)	1695.2	1271.4
Total carbon dioxide produced per round-trip (tonne-km)	5373.9	4030.4

With autonomous vessels having more efficient operation, there is a corresponding reduction of 25% in the CO_2 emissions. Proof that autonomous vessels are even an environmentally feasible option for humanitarian cargo transport.

6.4 Performance Assessment

6.4.1 Freight Rate

There is a prediction that there will be a 3.4% reduction in the cost of carrying freight (Kretschmann et. al, 2017) compared to a traditional vessel. Also, it is forecasted the global trade will expand by 2.4% (WTO, 2017), so if we assume that there is a technological improvement rate at the same pace for ocean transportation, a future prediction of performance can be estimated. In addition, probability distributions not shown in this report can be used to foresee outcomes regarding transportation performance, specifically in terms of costs.

For our study in Section 4.4.1, an estimation of the Maritime Transport Costs (OECD, 2010) from the United States (exporter) to Yemen (importer) are needed. The type of goods is assumed to be agriculture, particularly a cereals commodity, like wheat, and transported in bulk.

The three different measures for measuring maritime transport costs are in Table 23.

Table 23: Commodity Table (OECD, 2010)

	Importer country	Yemen
	Exporter country	United States
Type of Goods	**Commodity**	**Transport mode**
Agriculture	Cereals	Clean bulk

Table 24: Transport Cost Values (OECD, 2010)

	Year	
	2005	2006
Transport cost (USD)	28980532.87	29716178.54
Unit transport cost (USD/kg)	0.0514	0.0437
Ad valorem transport	0.266	0.2301

Using the unit transport cost value from the year 2006 and adjusting the rate by the global trade expansion rate in Table 24, the current value in the following years up to 2018 would be as follows:

$$tr_{unit} * (1 - r)^t = \$0.0437 * (1 - 0.024)^{12}$$

Equation 14: Calculating the Current Value of the Unit Transport Cost

Where r is the annual interest rate of 2.4% (in decimal form; matching the forecasted global trade growth), t is the time in years between 2006 and 2018 = 12 years.

In this case, the annual interest rate is used as a positive improvement in transport cost (i.e. a decrease in cost) per year.

Table 25: Estimated Unit Transport Cost

Year	Estimated unit transport cost (USD/kg)	Estimated unit transport cost (USD/MT)
2006	$0.0437	$43.70
2007	$0.0427	$42.65
2008	$0.0416	$41.63
2009	$0.0406	$40.63
2010	$0.0397	$39.65
2011	$0.0387	$38.70
2012	$0.0378	$37.77
2013	$0.0369	$36.87
2014	$0.0360	$35.98
2015	$0.0351	$35.12
2016	$0.0343	$34.28
2017	$0.0335	$33.45
2018	$0.0326	$32.65

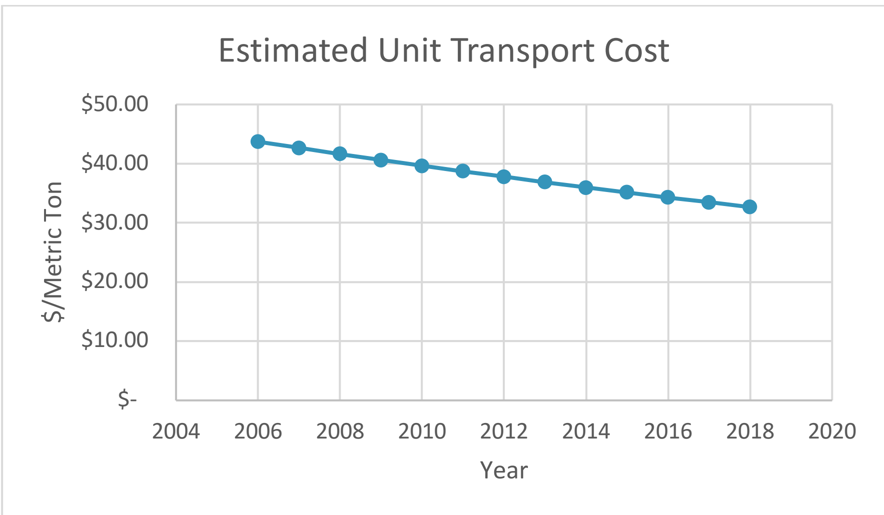

Figure 48: Estimated Unit Transport Cost

Due to the concept of autonomous vessels being relatively new, there is not much data readily available to analyze the realistic cost improvements of an unmanned vessel versus a traditional one. Although the assumption was made that the technological improvement rate will be in line with the global trade rate, this is still considered as large prediction and will need to be studied further.

7 Conclusion

As stated in a WMU report, automation in the maritime sector will by “evolutionary, rather than revolutionary”, meaning that the changes will be adapted over an extended period of time. Autonomous vessels are proven to be a more efficient solution in the transportation of passengers and cargo. They will allow for a reduction in operational costs due to an increase in the technology available to monitor and ensure sustainable propulsion. Additionally, crew will be reduced on board the vessel and replaced by automated technology means, decreasing operational costs tremendously.

In addition, there will be lowered fuel consumption and costs due to a lighter ship weight design and increase in fuel efficiency. A decrease in air resistance due to the absence of housing facilities will also serve as a method to decrease the overall total hull resistance. In closing, autonomous vessels can be applied in a humanitarian context, much like their “drone” counterparts. The vessel will serve the same purpose with transporting cargo and passengers, but there are still limitations of the report in that the concept of autonomous vessels is relatively new, especially for humanitarian emergency response. The autonomous vessel has the added benefit of being more environmentally friendly and cost-efficient in all contexts.

Not much data is available currently about automation and there needs to be more studies related to measuring the influence of varying automation degrees in the maritime sector. The approximations in this thesis may serve as the first step for MASS implementation on a larger scale.

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9 Appendices

9.1 Appendix A – MATLAB Code

9.1.1 Operational Costs

9.1.1.1 Air Resistance

```
clear
close all
clc

clear data

%Panamax Bulk Carrier (MUNIN report)
%   Breadth, Draft, Ballast, Design and Deckhouse Areas
breadth_m = 32;
draft_m = 14.5;

ballastarea_m = 617;
designarea_m = 422;
deckhousearea_m = 313;


%   Calculate proportions to apply the same to Handymax Design Vessel
%       Proportion of breadth to draft
P1 = breadth_m/draft_m;
%       Proportion of breadth to draft to ballast
P2 = P1/ballastarea_m;
%       Proportion of deckhouse area to frontal area when ballast
P3 = deckhousearea_m/ballastarea_m;
%       Proportion of ballast area to the design area
P4 = ballastarea_m/designarea_m;

%Apply the proportions to the Handymax Design Vessel
breadth_d = 32.24;
draft_d = 11;

ratio_d = breadth_d/draft_d;
ballastarea_d = ratio_d/P2;
designarea_d = ballastarea_d/P4;
deckhousearea_d = P3*designarea_d;

%Properties of the design vessel table
T = table(breadth_d,draft_d,ballastarea_d,designarea_d,deckhousearea_d);


% Calculate the air resistance in different design scenarios: ballast,
% design, autonomous
% air density, rho (kg/m^3) at sea level & 15 deg C
rho = 1.225;
% wind resistance coefficient, Cd  for the autonomous vessel a(adapted from
Blendermann, 1996 for a car carrier)
Cd_a = 0.45;
% wind resistance coefficient, Cd  for the traditional vessel t(adapted
from Blendermann, 1996 for a tanker)
Cd_t = 0.68;
% apparent wind speed, v_app = ship speed `+ true wind (m/s)
```

```
% true wind speed = 0.5 m/s in calm winds from the Beaufort wind scale
% ship speed = 15 knots = 7.717 m/s
v_app = 0.5 + 7.717;

% air density without considering frontal area (kg/(m*s^2) or Pa)
% for the autonomous vessel
Rw_a = (rho/2)*Cd_a*(v_app^2);
% for the traditional vessel
Rw_t = (rho/2)*Cd_t*(v_app^2);

% Aerodynamic force (N) of air in different design conditions
% for the autonomous vessel
Rw_a_ballastarea = Rw_a * ballastarea_d;
Rw_a_designarea =  Rw_a * designarea_d;
Rw_a_deckhouse = Rw_a * deckhousearea_d;

% Aerodynamic force (N) of air in different design conditions
% for the traditional vessel
Rw_t_ballastarea = Rw_t * ballastarea_d;
Rw_t_designarea =  Rw_t * designarea_d;
Rw_t_deckhouse = Rw_t * deckhousearea_d;


%Results Table for Air Resistance
T2 = table(Rw_a_ballastarea, Rw_a_designarea, Rw_a_deckhouse,
Rw_t_ballastarea, Rw_t_designarea, Rw_t_deckhouse);
```

9.1.1.2 Forecasted Fuel Costs

```
clear
close all
clc

clear data
data = load('Bunker_prices.txt');

% Bunker price trends for IFO180 and MGO (Ship & Bunker, 2019)
    yearx = data(:,1); %Excel Date - Year from January 2016 - January 2018
    year = x2mdate(yearx,1);   %Convert to Excel date to MATLAB date


ifo_price = data(:,2); %# IFO 80 Global Ports Average (Singapore,
Rotterdam, Fujairah and Houston)
mgo_price = data(:,3);%# MGO Global Ports Average (Singapore, Rotterdam,
Fujairah and Houston)
format long

%   Table of IFO 80 and MGO price by date
T_bunker = table(year,ifo_price, mgo_price);

%Simple Linear Regression for IFO & MGO
%   Calculate b1 =  the slope or regression coefficient
b1_ifo = year\ifo_price;
b1_mgo = year\mgo_price;
%   Linear relation
yCalc1_ifo = b1_ifo*year;
yCalc1_mgo = b1_mgo*year;

X_ifo = [ones(length(year),1) year];
```

```
X_mgo = [ones(length(year),1) year];

%   Add y-intercept into the model, b
b_ifo = X_ifo\ifo_price;
b_mgo = X_mgo\mgo_price;

yCalc2_ifo = X_ifo*b_ifo;
yCalc2_mgo = X_mgo*b_mgo;

% Forecasted Growth in Bunker prices based on growth average growth
% Processing Year Range in MATLABDate format
%year2 = x2mdate(43474:56979)';
year2 = (43474:56979);
s = length(year2);

% Starting - Bunker Prices from 09/Jan 2019
ifo_start = 412;
mgo_start = 597;

% Iteration to solve for future IFO 80 and MGO prices
%for i = 2:s
    %ifo_forecast(i) = (.01*b1_ifo)*ifo_start(i-1);
    %mgo_forecast(i) = (.01*b1_mgo)*mgo_start(i-1);

 %end

figure;
grid on
hold on
scatter(yearx,ifo_price)
scatter(yearx,mgo_price)
plot(yearx,yCalc1_ifo,yearx,yCalc1_mgo,yearx,yCalc2_ifo,yearx,yCalc2_mgo)
xlabel('Year')
ylabel('Price (USD)')
title('Linear Regression Relation Between Price & Year')
grid on
legend('IFO 80 Price','MGO Price','IFO Slope','MGO Slope','IFO Slope &
Intercept', 'MGO Slope & Intercept')
datetick('x','yyyy','keepticks')
hold off


%   Plot of IFO 80 & MGO Prices by Year
figure;
grid on
hold on
plot(yearx,ifo_price,yearx,mgo_price,'--','linewidth',1.5);
legend('IFO 80 price','MGO price')
legend('Location','southeast')
title('IFO 80 and MGO Prices')
xlabel('Year')
%xlim([2015 2019])
ylabel('Price (USD)')
ylim([0 800])
datetick('x','yyyy','keepticks')
```

9.1.2 Environmental Analysis

9.1.2.1 Shipping Emissions Data

```
clear
close all
clc

clear data
data = load('shipping_emissions.txt');

%Current CO2 Shipping Emissions Data (ITF, 2017)
year = data(:,1);   %Year
global_CO2 = data(:,2); %Global CO2 emissions per  year
international_CO2 = data(:,3);  %International Shipping CO2 emissions per
year
total_CO2 = data(:,4);  %Total Shipping CO2 emissions per year

%   Table of Current CO2 Shipping Emissions
T = table(year,international_CO2,total_CO2,global_CO2);


%   Plot of Current CO2 Shipping Emissions
figure;
grid on
hold on
plot(year,international_CO2,year,total_CO2,'r-','linewidth',1.5);
title('International and Total Shipping Emissions')
xlabel('Year')
xlim([2006 2016])
yyaxis left
ylabel('CO2 Emissions (million tonnes)')
ylim([0 1200])

%   Growth rate per year of Global CO2 Emissions
%       Growth rate per year
growth_global = [global_CO2(2:end)./global_CO2(1:end-1)-1];
%       Average growth rate
av_growth_global = mean(growth_global);

%   Percentage Total Shipping Emissions in Global CO2 Emissions per year
perc_total = (total_CO2./ global_CO2)*100;
%       Average percentage of Total Shipping emissions between 2007 - 2015
av_total = sum(perc_total)/length(perc_total);
%       Growth rate per year (percentage)
growth_total = [total_CO2(2:end)./total_CO2(1:end-1)-1]*100;
%       Average growth rate (percentage)
av_growth_total = mean(growth_total);

%   Percentage International Shipping Emissions in Total per year
perc_int = (international_CO2./ global_CO2)*100;
%       Average percentage of Global emissions between 2007 - 2015
av_int = sum(perc_int)/length(perc_int);
%       Growth rate per year (percentage)
growth_int = [international_CO2(2:end)./international_CO2(1:end-1)-1]*100;
%       Average growth rate (percentage)
av_growth_int = mean(growth_int);

%   Plot of the Percentage of Total Shipping Emissions in Global context
yyaxis right
ylabel('Total Shipping Emissions Globally (%)')
```

```
ylim([0 4.0])
plot(year,perc_total,'m-','linewidth',0.5)
legend('International Shipping Emissions','Total Shipping
Emissions','Shipping % of Global Emissions')
hold off

%Forecasted Growth in International Shipping Emissions (if nothing changes)
%Linear Regression of International Shipping Emissions
%   Compute the slope/regression coefficient
b1 = year\international_CO2;

%   Compute emissions per year yCalc from x using relation
%   Evaluate until year 2055 by creating year2 variable
year2 = (2015:2055)';
yCalc1 = b1 * year;
y2Calc1 = b1 * year2;

figure;
grid on
hold on
plot(year,yCalc1)
plot(year2,y2Calc1,'r-','linewidth',1.5)
scatter(year,international_CO2)
legend('Slope','International Emissions')
title('Forecasted Growth in International Shipping Emissions')
xlabel('Year')
xlim([2006 2056])
ylabel('CO2 Emissions (million tonnes)')
ylim([0 1200])


% Forecasted Growth in International Shipping Emissions based on growth in
% average growth in global CO2 Emissions between 2007 and 2015
year2 = (2015:2055)';
s = length(year2);

% Starting - Emissions in 2015
global_CO2_forecast = 36062;
total_CO2_forecast = 932;
international_CO2_forecast = 812;

% The International Transport Forum (ITF) prediction of 3% annual growth
rate
av_ITF = 0.03;
%ITF_CO2_forecast(i) = (av_ITF)*global_CO2_forecast(i-1);

% Iteration to solve for future CO2 emissions
for i = 2:s
    global_CO2_forecast(i) = (1 + av_growth_global)*global_CO2_forecast(i-
1);
    total_CO2_forecast(i) = (.01*av_total)*global_CO2_forecast(i-1);
    international_CO2_forecast(i) = (.01*av_int)*global_CO2_forecast(i-1);
end

%Plot of international and total shipping emissions predictions
figure;
grid on
hold on
%plot(year,global_CO2)
%plot(year2,global_CO2_forecast)
```

```
plot(year,total_CO2,'linewidth',2.5)
plot(year2,total_CO2_forecast,'linewidth',2.5)
plot(year,international_CO2,'r-','linewidth',2.5)
plot(year2,international_CO2_forecast,'linewidth',2.5)
%plot(year2,ITF_CO2_forecast)
legend('Total Shipping CO2 Emissions', 'Forecasted Total Shipping CO2
Emissions','International CO2 Emissions','Forecasted International Shipping
CO2 Emissions')
legend('Location','southeast')
title('Forecasted Growth in Shipping Emissions')
xlabel('Year')
xlim([2000 2060])
ylabel('CO2 Emissions (million tonnes)')
ylim([0 2000])


%------------------------------
clear
close all
clc

clear data
data = load('fleet_data.txt');

%Current Global Fleet Data (UNCTAD, 2018) & CO2 Shipping Emissions Data
(ITF, 2017)
year_fleet = data(:,1); %Year from 2011-2014
fleet_num = data(:,2); %# of ships in the global fleet
dwt_num = data(:,3); %# of DWTs total in 1000s
global_CO2 = data(:,4); %Global Shipping CO2 emissions per year
international_CO2 = data(:,5);  %International Shipping CO2 emissions per
year
total_CO2 = data(:,6);  %Total Shipping CO2 emissions per year

%   Table of Current CO2 Shipping Emissions
T_fleet = table(year_fleet,fleet_num,
dwt_num,global_CO2,international_CO2,total_CO2);
```

9.1.2.1 World Merchant Fleet

```
clear
close all
clc

clear data
data = load('fleet_data.txt');

%Current Global Fleet Data (UNCTAD, 2018) & CO2 Shipping Emissions Data
(ITF, 2017)
year_fleet = data(:,1); %Year from 2011-2014
fleet_num = data(:,2); %# of ships in the global fleet
    fleet = fleet_num/1000; % so data can be in 1000s
dwt_num = data(:,3); %# of DWTs total in 1000s
global_CO2 = data(:,4); %Global Shipping CO2 emissions per year
international_CO2 = data(:,5);  %International Shipping CO2 emissions per
year
total_CO2 = data(:,6);  %Total Shipping CO2 emissions per year
format long
```

```
%   Table of Fleet, DWT and global, international and total shipping CO2
T_fleet = table(year_fleet,fleet,
dwt_num,global_CO2,international_CO2,total_CO2);

%   Simple Linear Regression Model with World Merchant Fleet Data
%       Calculating the slope (regression coefficient)
b1 = year_fleet\fleet_num;
yCalc1 = b1*year_fleet;
    yCal = yCalc1/1000; %so data can be in 1000s
%       Improve the fit with a y-intercept
X = [ones(length(year_fleet),1) year_fleet];
b = X\fleet;
yCalc2 = X*b;

%   Plot of year vs fleet
figure;
grid on
hold on
plot(year_fleet,yCal,year_fleet,fleet,year_fleet,yCalc2,'--
','linewidth',1.5);
legend('Slope','# of Ships (in 1000s)','Slope & Intercept')
legend('Location','southeast')
title('World Merchant Fleet')
xlabel('Year')
xlim([2010 2015])
ylabel('Number of Ships (in 1000s)')
ylim([80 90])
a = axis;
set(gca, 'XTick', 2010:2015)
ay = gca;
ay.YRuler.Exponent =0;



%   Multiple Linear Regression
x1 = fleet_num;
x2 = total_CO2;
y = year_fleet;
X1 = [ones(size(x1)) x1 x2 x1.*x2];
b = regress(y,X1);

figure;
scatter3(x1,x2,y,'filled')
hold on
x1fit = min(x1):100:max(x1);
x2fit = min(x2):10:max(x2);
[X1FIT,X2FIT] = meshgrid(x1fit,x2fit);
YFIT = b(1) + b(2)*X1FIT + b(3)*X2FIT + b(4)*X1FIT.*X2FIT;
mesh(X1FIT,X2FIT,YFIT)
xlabel('# of Fleet')
ylabel('Total Shipping Emissions')
zlabel('Year')
view(50,10)
hold off
```

9.1.2.2 Shipping Emissions Calculator

```
clear
close all
clc
```

```
%Input paramenters
% W (metric tons (MT)) = the cargo payload carried from Port A to B
%   function of ship's deadweight and the upper bound is used, capacity
utilization
% L (km) = distance between Port A and B
% V (km/day) = speed when going laden (loaded) from A to B
%   average speed assumed for sea voyage
% v (km/day) = speed when returning empty on ballast
% T (days) = ship time spent loading at Port A
%   based on port surveys for dry bulk vessel from the Entec Ship Emissions
report
% t (days) = ship time spent discharging at Port B
% D (days) = ship operational days per year
% w = average cargo carrying capacity assumed for all sea legs (0<w<1)
%   for example, ship travels full in one direction and empty on ballast, w
%   = 0.5
W = 25000;
L = (8124)*1.852;
V = (15)*44.45;
v = (15)*44.45;
T = 47/2/24;
t = 47/2/24;
D = (0:5:270)';
w = 0.5;

%Assuming fuel consumptions are known (tonnes/day)
% G = at loading port
%   average fuel consumption at port
% g = at discharging port
% F = at sea, laden
%   average fuel consumption for at sea voyage
% f = at sea, on ballast
%   both are functions of speeds V and v, respectively
%   both are proportional to the cube of V and v, respectively
%   both are functions of the horsepowers that are sailing laden and on
ballast speeds at V and v, respectively
G = 27;
g = 27;
F = 27;
f = 27;

%Compute variables:
% TTab (days) = transit time from A to B
% TTba (days) = transit time from B to A
% TFC (MT) = total fuel consumption per round-trip
% TTkm (MT-km) = total tonne-km's carried per round-trip
% TCO2 (MT-km) = total carbon dioxide (CO2) produced per round-trip
%   MT-km = (cargo carried while laden) * distance
%   zero MT-km's registered during the ballas leg o the trip
TTab = L/V;
TTba = L/v;
TFC = G*T + ((F*L)/V) + g*t + ((f*L)/v);
TTkm = W*L;
TCO2 = 3.17*(G*T + (F*L)/V + g*t + ((f*L)/v));

% s = fraction of operational days the ship is at sea
% I (days) = idle days in a year
% p = fraction of D the ship is at port
% sD (days) = days at sea in a year
% pD (days) = days at port in a year
```

```
s = (D/365)';
I = 365 - D;
p = 1-s;
sD = s*D;
pD = p*D;

% sDV (km) = sea kilometers in a year
% TFCy (MT) = total fuel consumption in a year
% TCO2y (MT) = total CO2 in a year
% TTkmy (MT-km) = total tonne-km's in a year
%   computed by multiplying the average payload carried by the ship when at
%   sea (wW) by the total sea kilometers traveled by the ship in a year
%   (SDV)
% CO2km = total CO2 per MT-km
sDV = s*D*V;
TFCy = (s*F + p*G)*D;
TCO2y = 3.17*(s*F + p*G)*D;
TTkmy = (w*W)*(s*D*V);
CO2km = 3.17*(F + (p/s)*G)/w*W*V;t

%Construct table based on data
Table = table(TFC, TCO2);
```