Sustainability of maritime supply chain; economic analysis to comply with environmental regulations and social issues

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January 2022

Cover: Majid Mohseni

Printing: Universitas, Antwerp

ISBN: 9789057287312

Deposit number: D/2022/12.293/03

The content, analysis, and views set out and expressed in this doctoral thesis reflect only the author's opinion.

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List of Abbreviations

AFS	Anti-fouling Systems
AI	Artificial Intelligence
BWE	Ballast Water Exchange
BWM	Ballast Water Management
BWMS	Ballast Water Management System
BWRS	Ballast Water Risk Assessment
CCM	Chain Cost Model
CFD	Computational Fluid Dynamics
CII	Carbon Intensity Indicator
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CR	Customer Requirements
CSI	Container Security Initiative
CSR	Corporate Social Responsibility
C-TPAT	Customs and Trade Partnership against Terrorism
DME	Dimethyl Ether
DR	Design Requirements
ECA	Emission Control Area
EDI	Electronic Data Interchange
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
ENS	Entry Notification Summary
EPI	Environmental Performance Indicators
ERP	Enterprise Resource Planning
EU	European Union
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
GHG	Greenhouse Gas
HDRD	Hydrogenation-Derived Renewable Diesel
HFO	Heavy Fuel Oil
HSFO	High Sulfur Fuel Oil
IAPH	International Association of Ports and Harbors
IFO	Intermediate Fuel Oil
ILRP	Inventory Location Routing Problem
IMO	International Maritime Organization
IoT	Internet of Things
ISM	International Safety Management
ISPS	International Ship and Port Facility Security
IT	Information Technology
LCA	Life-Cycle Assessment
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSFO	Low Sulfur Fuel Oil
MARPOL	International Convention for the Prevention of Pollution from Ships
MarSC	Maritime Supply Chain
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MFRP	Maritime Fleet Renewal Problem
MGO	Marine Gasoil
NO_X	Nitrogen Oxides

NUTS	Nomenclature of territorial units for statistics
OCR	Optical Character Recognition
OPEX	Operating Expense
OPRC-HNS	Convention on Oil Pollution Preparedness, Response, and Co-operation regarding Hazardous and Noxious Substances
PM	Particulate Matter
RPM	Revolution Per Minute
SECA	Sulfur Emission Control Area
SOLAS	International Convention for the Safety of Life at Sea
SO_x	Sulfur Oxides
SRA	Same Risk Area
STCW	Standards of Training, Certification and Watch keeping for Seafarers
TEU	Twenty-foot Equivalent Unit
ULSD	Ultra-Low-Sulfur Diesel
UN SDG	United Nations Sustainable Development Goal
VMI	Vendor Managed Inventory
VOC	Volatile Organic Compounds

Biography of Author

My academic background lies in Mathematics and Civil Engineering; after graduating with my Bachelor's degree in Civil Engineering from Azad University in Tehran in September 2013, I was accepted for the Master's degree in Civil Engineering for Risk Mitigation at the University Politecnico di Milano in Italy which I received the gold scholarship from the faculty. During my Master's program, I had a great chance to take excellent courses and work with outstanding professors related to designing and structural analysis and related to the transport systems and transport risk, transport management in emergency planning, and tools for risk management. I successfully defended my Master's thesis in December 2017 with the thesis title *social-economic evaluation of congestion cost in different roads* supervised by Prof. Paolo Beria. This thesis developed a parametric methodology to estimate congestion's excess burden, based on supply-demand curve and comparison of obtained results with congestion cost appraised based on 'annual average daily traffic' applied in some road networks in the Trentino Alto-Adige region in Italy as case studies.

A couple of months later, I started my Ph.D. track at the University of Antwerp in March 2018. My Ph.D. study program covered several aspects of the maritime supply chain as the hinterland, shipping companies, ports, policy-making for sustainable maritime supply chain, and sustainability in regional, national and global maritime supply chain.

Next to my Ph.D. thesis, I worked on different projects such as WP3 and WP4 of the Clusters 2.0, a Horizon 2020 project leveraging the potential of European Logistics Clusters for a sustainable, efficient, and fully functional integrated transport system. Moreover, I was also engaged in the FERRMED project - the study of traffic and modal shift optimization in the EU core network - focusing on Trans-Eurasian primary railway network enhancement. Next to that, I did research on the Belt and Road Initiative (BRI) World Bank project to assess the competitiveness of Greece as a gateway for intercontinental (primarily Asia-Europe) containerized freight to/from Central Europe compared to routings using gateways in other European countries which lead to conduct logistics costs and logistics performance modeling.

I believe it is an outstanding achievement to accomplish the Ph.D. program in the scheduled time, which was four years. Since the beginning of my Ph.D. journey, I have always stuck to the plan to defend my Ph.D. on time, and I am so grateful that my hard and intelligent work led to this significant result, and I achieved this ambition.

Acknowledgment

Fulfilling a Ph.D. program and being a researcher in academia is one of the most challenging experiences in everybody's life. It is full of uncertainties, hardworking, taking initiatives, and more importantly, it becomes more difficult if you are from a different academic background.

After successfully graduating with my Master's degree in a top-ranked University in Civil Engineering – Politecnico di Milano – I started my doctoral program in maritime transportation at the University of Antwerp, renowned and outstanding in this industry. I faced different educational and research experiences and challenges that helped me improve myself in real life to overcome the difficulties.

Therefore, first of all, I want to thank myself for being hardworking, dedicated, responsible, and never giving up on the difficulties of life, especially in a four-year Ph.D. program.

In addition, I would like to thank my supervisors, Prof. Edwin van Hassel and Prof. Thierry Vanelslander, for their guidance and advice during my Ph.D. track. Moreover, I would like to thank the jury members of Ph.D. committed, namely Prof. Sys, Prof. Serra, Prof. Van Passel, Dr. Michail, and Dr. van der Horst, for providing positive and constructive comments that made my doctoral thesis more important and valued.

Moreover, from the bottom of my heart, I would like to express my ultimate gratitude to my family; especially my mother *Malak*, my father *Reza*, my older brother *Mammad* and my younger brother *Saeed* for their support and encouragement in my life who always get my back when I need them and are my loved-ones and my tangible assets in this world.

Also, special thanks go to my friends, professors, teachers, and anyone who assisted me and had a good impression on my life.

In addition, I would like to thank Politecnico di Milano University and the Department of Transport and Regional Economics of the University of Antwerp for providing the chance for me to pursue my academic carrier.

I would like to dedicate this Ph.D. to the soul of my mother, Malak, who is always in my heart.

Also, to the souls of 176 beautiful people who perished on January 8^{th,} 2020, in Ukraine International Airlines Flight PS752, when the plane shut down shortly after the take-off.

Abstract

Maritime transport is considered the most significant transport mode in world trade, and maritime trade has risen in recent years, which leads to economic growth. However, at the same time, it causes severe environmental effects that jeopardize the ecosystem and human health. The adverse impacts of the maritime supply chain (MarSC) are not limited to greenhouse gas (GHG) emissions and air pollution. Still, they include other significant issues such as spreading invasive species via ballast water, oil spills, chemical and waste management, cargo handling, safety and security at the ports, and noise pollution.

The sustainability of this sector is a challenging issue for the stakeholders involved in this industry. Several aspects are indispensable to enhancing the sustainability of MarSC, grouped as economic, social, and environmental elements. In this thesis, some of the main significant issues in containerized maritime shipping are addressed economically, in which the main objective is to improve the sustainability of MarSC under environmental and social regulations. This Ph.D. covers different segments and stages of the MarSC, including hinterland transport, seawaters, maritime shipping, and port and terminal operations to improve the sustainability of the MarSC at regional, national, and global levels.

The main objective of this Ph.D. is to provide the economic assessment of the most selected and promising technologies and methodologies to overcome the negative impacts of the marine shipping and port industry and bridge some of the available shortcomings. Besides, it will enhance the sustainability of maritime shipping in terms of economic, environmental, and social perspectives concerning the current international conventions and legislation. The overarching research question is: What is the economic impact of sustainability issues on maritime shipping in various trade routes from different stakeholders’ standpoints?

This Ph.D. thesis is based on an application approach, and each one is researched in an independent chapter in which several methodologies are applied to fulfill the objectives and respond to the key research question. Four main application studies are as follows: economic impact of the installment of Same Risk Area (SRA) under the Ballast Water Management Convention (BWMC), economic evaluation of alternative technologies to mitigate sulfur emissions, enhancing the supervision of containerized cargo from an economic perspective and supply chain analysis in terms of dry and reefer cargo.

The Chain Cost Model (CCM) is the primary model, and it calculates the generalized cost per TEU in a loop. Then, a novel typology of vessel types is developed based on yearly BW consumption and previous vessels' call port. The applied methodology is the cost and benefit calculation of the ships based on the obtained typology leading to the total net benefit of installing the SRA. Next, a unique scanning cost approach is established to assess the scanning costs based on various scanning rates and locations.

This Ph.D. supports the governments and policy-decision makers by providing the costs and benefits of selected cases of addressing the sustainability of MarSC. Moreover, the outcomes are beneficial for a large group of maritime stakeholders, including port authorities, terminal operators, customs brokers, shipping companies, shippers, and academia.

Abstract in Dutch

Zeevervoer wordt beschouwd als de belangrijkste vervoerswijze in de wereldhandel en de maritieme handel is de afgelopen jaren toegenomen, wat leidt tot economische groei. Tegelijkertijd veroorzaakt het echter ernstige milieueffecten die het ecosysteem en de menselijke gezondheid in gevaar brengen. De nadelige effecten van de maritieme toeleveringsketen (MarSC) zijn niet beperkt tot de uitstoot van broeikasgassen en luchtvervuiling, maar omvatten andere belangrijke problemen zoals de verspreiding van invasieve soorten via ballastwater, olielozingen, chemicaliën en afvalbeheer, vrachtafhandeling, veiligheid en beveiliging in de havens en geluidsoverlast.

De duurzaamheid van deze sector is een uitdagend vraagstuk voor de stakeholders die betrokken zijn bij deze sector. Verschillende aspecten zijn onmisbaar om de duurzaamheid van MarSC te vergroten, gegroepeerd als economische, sociale en ecologische elementen. In dit proefschrift worden enkele van de belangrijkste belangrijke problemen in de gecontaineriseerde zeevaart economisch aangepakt, waarbij het belangrijkste doel is om de duurzaamheid van MarSC onder milieu- en sociale regelgeving te verbeteren. Dit doctoraat bestrijkt verschillende segmenten en stadia van de MarSC, waaronder vervoer via het achterland, zeewater, zeescheepvaart en haven- en terminalactiviteiten om de duurzaamheid van de MarSC op regionaal, nationaal en mondiaal niveau te verbeteren.

Het hoofddoel van deze Ph.D. is om de economische beoordeling te geven van de meest geselecteerde en veelbelovende technologieën en methodologieën om de negatieve effecten van de zeescheepvaart en havenindustrie te overwinnen en enkele van de beschikbare tekortkomingen te overbruggen. Bovendien zal het de duurzaamheid van de zeescheepvaart vergroten in termen van economische, ecologische en sociale perspectieven met betrekking tot de huidige internationale verdragen en wetgeving. De overkoepelende onderzoeksvraag is: Wat is de economische impact van duurzaamheidsvraagstukken op de zeescheepvaart in verschillende handelsroutes vanuit het standpunt van verschillende stakeholders?

Dit doctoraat thesis is gebaseerd op een toepassingsbenadering, en elk ervan wordt onderzocht in een onafhankelijk hoofdstuk waarin verschillende methodologieën worden toegepast om de doelstellingen te bereiken en om de belangrijkste onderzoeksvraag te beantwoorden. Vier belangrijke toepassingsstudies zijn als volgt: economische impact van de installatie van Same Risk Area (SRA) onder de Ballast Water Management Convention (BWMC), economische evaluatie van alternatieve technologieën om zwavelemissies te verminderen, verbetering van het toezicht op containerlading vanuit een economisch perspectief en supply chain-analyse in termen van droge en reeferlading.

Het Chain Cost Model (CCM) is het primaire model en berekent de gegeneraliseerde kosten per TEU in een lus. Vervolgens wordt een nieuwe typologie van scheepstypen ontwikkeld op basis van het jaarlijkse BW-verbruik en eerdere aanloophavens van schepen. De toegepaste methodiek is de kosten- en batenberekening van de schepen op basis van de verkregen typologie die leidt tot het totale nettovoordeel van het installeren van de SRA. Vervolgens wordt een unieke scankostenbenadering vastgesteld om de scankosten te beoordelen op basis van verschillende scansnelheden en locaties.

Dit doctoraat ondersteunt de regeringen en beleidsmakers door de kosten en baten te verstrekken van geselecteerde gevallen van het aanpakken van de duurzaamheid van MarSC. Bovendien zijn de resultaten gunstig voor een grote groep maritieme belanghebbenden, waaronder havenautoriteiten, terminaloperators, douane-expediteurs, rederijen, verladers en de academische wereld.

Chapter 1: Introduction

Maritime transport is considered the most significant transport mode in world trade. However, the sustainability of this sector is a challenging issue for the stakeholders involved in this industry and specifically for port authorities and shipping companies. Several aspects are indispensable to enhancing the sustainability of the maritime supply chain (MarSC), grouped as economic, social, and environmental elements. It involves costs and benefits of innovative technologies, ballast water treatment, air pollution reduction, considering alternative fuels rather than Heavy Fuel Oil (HFO), greenhouse gas (GHG) emissions, maritime safety and security, illicit trafficking through the ports, skilled employees for future trends, job satisfaction rate, and the adaptability of these technologies to the existing ships.

It is observed that maritime shipping and trade have risen in recent years, which leads to economic growth. However, at the same time, it causes severe environmental effects that jeopardize the ecosystem and human health. The adverse impacts of MarSC are not limited to GHG emissions and air pollution, but they include other significant issues such as the spread of invasive species via ballast water, oil spill, chemical and waste management, cargo handling, safety and security at the ports, and noise pollution to mention a few.

In this thesis, some of the main significant issues in containerized maritime shipping are addressed economically, in which the main objective is to improve the sustainability of MarSC under environmental and social regulations.

This chapter defines MarSC, stakeholders involved in the industry, and sustainability of MarSC along with its dimensions, namely economic, environmental and social. Besides, the Sustainable Development Goals (SDGs) are defined and discussed with their ties with this Ph.D. thesis. Also, the trends in the MarSC's sustainability are explained based on the International Association of Ports and Harbors (IAPH) projects. In addition, the adverse effects of marine shipping on the environment and the most substantial regulations and legislations to overcome them are addressed. Subsequently, to provide a general overview of the thesis, the main research questions and a brief explanation of the applied methodology of each chapter are argued.

1.1. Maritime supply chain (MarSC)

Maritime shipping is considered an essential and indispensable element of facilitating global trade through connecting producers, manufacturers, and consumers (Cicek, Akyuz, & Celik, 2019; Lam, 2015; Parthibaraj, Subramanian, Palaniappan, & Lai, 2018; Ren & Lützen, 2017; Zheng, Hu, & Dai, 2013), which ensures the continuous growth of seaborne trade (Yang, Wang, & Li, 2013) and plays a critical role in providing low-cost, environment-friendly and efficient transportation as well as in connecting global economy and driving economic prosperity (Lam, 2011; Lun, Lai, Wong, & Cheng, 2013; Yang et al., 2013). The maritime transport network is built based on vessel characteristics, ports of call, and vessel movements (Liu, Tian, Huang, & Yang, 2018).

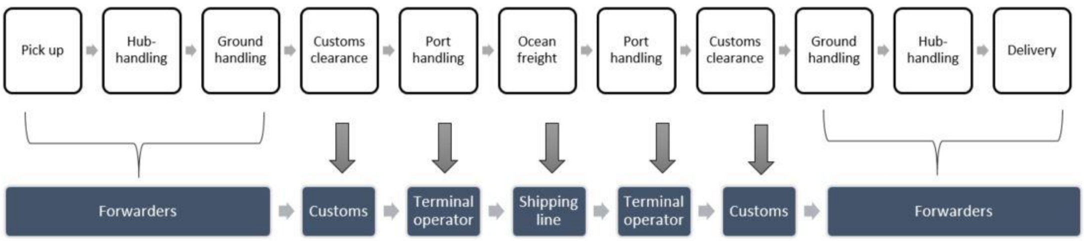
Lam (2011) defines the MarSC in the context of container shipping as "*the connected series of activities of shipping services which are concerned with planning, coordinating, and controlling containerized cargoes from the point of origin to the point of destination*," aiming to add value to the goods transported (Lam, 2015).

Green supply chain management is defined as a firm's plans and activities that assimilate environmental concerns into supply chain management to improve the environmental performance of suppliers and customers (Bowen, Cousins, Lamming, & Faruk, 2001). Green shipping refers to the environmentally friendly commercial and non-commercial seafaring activities (Jasmi & Fernando, 2018) to manage and monitor all harmful substances emitted from ships (Im et al. 2005), including reducing emissions and marine pollution resulting from decreasing the negative impacts to the environment (Jasmi & Fernando, 2018). Compliance for energy-saving shipping equipment design, shipping equipment reuse, recycling, and recovery of waste, and reduction of environmental damages are green shipping practices for shipping firms (hung Lai, Wong, Veus Lun, & Cheng, 2013). One of the critical drivers for shipping firms to adopt green operations is performance, which comprises economic and environmental dimensions (Venus Lun, Lai, Wong, & Cheng, 2015).

1.2. Stakeholders in the MarSC

MarSC includes various stakeholders and several operations and stages. The MarSC process is plotted in Figure 1.1.

Figure 1. 1: MarSC process



Source: Authors' composition based on Veenstra, Hintsa, and Zomer (2008) and SMART-CM D1.2.1 (2009); Davydenko et al. 2014; Garg and Kashav 2019

In the freight forwarding stage, the stakeholders are exporters, cargo packing companies, shipping lines, freight forwarders, agents, inland port companies, warehousing companies, etc., typically responsible for the first and the last mile of the supply chain. In the Customs stage, Customs are responsible for providing the customs clearance of the containers and cargo.

Port handling of containers is carried out in the terminal operator's stage. In the fourth stage, shipping lines are the carriers for carrying the containers through oceans. Also, some stakeholders at seaports are stevedoring companies, bunkering companies, dredging, towage, and pilotage service companies (Garg & Kashav, 2019). The structure of MarSC members is defined and categorized by several scholars and plotted in Table 1.1.

Table 1. 1: MarSC stakeholders

Stakeholders	Definition
Shipper	Known as freight owner or consignor seeking for transportation of its goods closer to the users of goods
Carrier	Including operator and shipping line (international and domestic operations) and airlines carrier
Shipowner	Seeking business goals such as return on ship investment with the role of selling or chartering the capacity
Terminal operator	Including maritime port, inland port system, freight terminal, and inland container depot
Carrier intermediaries	Including shipping agents, air cargo agents, off-dock depot operators, non-vessel operating common carriers, shipbrokers, and inland-ports
Cargo intermediaries	Including freight forwarders, customs agents, multimodal transport operators, warehouse operators (bonded and non-bonded), private warehouses (bonded and non-bonded), international procurement centers, and regional distribution centers
Inland water transport	Including barges, tugs, and riverine vessels
Rail transport services	Railway operation system for transporting cargo
Road transport services	Road haulers (conventional trucking, container truck transportation, and bonded truck)
Ancillary services	Providers including cargo handlers or stevedoring companies, packaging service providers, cargo consolidators, and equipment maintenance and material handling suppliers
Integrated logistics service providers	Including third-party logistics providers (3 PLs) and lead logistics providers (LLPs), often called fourth-party logistics providers (4PLs)

Source: Authors' composition based on Jasmi and Fernando 2018; Schwartz et al. 2020

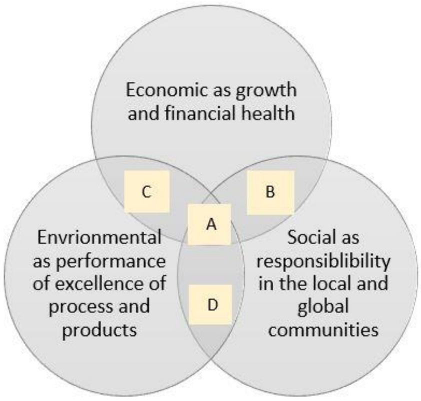
In containerized shipment, shippers, liners, port, terminal operators, and inland transport providers are primary members (Lam and van de Voorde 2011) in which shippers, shipping lines, and ports are in the chain are vertically linked by customer-supplier relationships (Lam, 2011).

1.3. Sustainability in MarSC

Sustainable supply chain management is predetermined as the strategic integration of economic, environmental, and social goals for the improvement of the economic performance of an organization (Carter and Rogers 2008; C.C. Cheng et al. 2014; Acciaro 2015; Mani et al. 2016; P. T. W. Lee et al. 2019), and in operational and managerial processes (Kim & Chiang, 2014). Sustainability assessment requires the simultaneous balancing of the economic performances, environmental effects, and social impacts in policy, decisions, and general management of any organizational function (Cheng, Farahani, Lai, & Sarkis, 2015; Psaraftis, 2016; Ren & Lützen, 2017).

Jiménez- González & Woodley (2010) consider the dimensions of sustainability through a triple bottom line assessment that covers economic, environmental, and social aspects (A). The relation between economic and social dimensions is called socio-efficiency (B), while the relation between economic and environment is known as eco-efficiency (C) and the relation between social and environment is eco-social balance (D).

Figure 1. 2: Sustainability dimensions of MarSC



Source: Authors' composition based on Jiménez- González and Woodley 2010

Lam & van de Voorde (2011) suggest that customer focus is a significant attribute contributing to a MarSC's total value and leads shipping companies to achieve sustainability and enhance their competitiveness. Bansal and DesJardine (2014) characterize the corporate sustainability (CS) concept as the integration of three domains of society, environment, and economy in the long-term and aiming at strengthening links between them through improving water use and energy efficiency, reducing GHG emissions, reducing or zero-waste, increasing resilience to climate change, minimizing impacts to biodiversity and natural resources, enhancing human capital and capability, and achieving greater social inclusion.

Interestingly, Cheng et al. (2015) define the sustainable MarSC as ''integrating maritime organizational units (ports, shipping companies, etc.) along a supply chain and coordinating materials (container, bulk, and general cargoes), information, and financial flows to (a) fulfill customer demands to improve the competitiveness of the supply chain as a whole to make profit subject to compliance with regulations to control (b) social and (c) environmental impacts''. In other words, sustainable shipping covers the dimensions of (i) economic (profit), (ii) environmental (the planet), and (iii) social (people).

1.3.1. Economic sustainability

A sustainable economy is defined as an economy that is able ''to satisfy the needs of the present generation without compromising the ability of future generations to meet their own needs'' (Cheng et al. 2013). A sustainable supply chain has to be economically viable and, in particular, possess the capability to increase profitability (Pagell and Wu, 2009). Supply chain optimization maximizes product values with minimum raw materials, inventory, and production costs (Büyüközkan and Berkol, 2011). For a MarSC, Lam & van de Voorde (2011) noted that the goal is to synchronize the processes and partners to generate maximum profits. From the economic aspect of sustainability, price competition is the main decisive factor in the maritime industry (Lam et al. 2013). The challenge to attain a sustainable economy is to pursue economic growth while ensuring environmental protection (Cheng et al. 2013).

1.3.2. Environmental sustainability

In contrast to the economic aspect, the environmental dimension of sustainability is widely addressed in the literature, combining both social and economic perspectives and mainly concerning ships and port equipment (Lee et al., 2019). The sustainability issues for the shipping and port sector are related to green ports and shipping, carbon emission, climate change, and region-specific environmental regulation and management (Shin et al. 2018). Furthermore, mitigation of other emissions such as nitrogen oxides (NO_X), sulfur oxides (SO_x) emissions, ballast water treatment, etc., play an essential role in improving the MarSC. As only economic performance is insufficient for long-term sustainability, environmental sustainability has become a popular topic among academics and industries in the MarSC (Lee and Lam, 2012). Reducing CO_2 emissions is an essential issue for the container shipping industry in achieving its environmental sustainability (Qi & Song, 2012).

1.3.3 Social sustainability

Asgari, Hassani, Jones, and Nguye (2015) define the social issues in the supply chain as product or process-related aspects of operations that affect human safety, welfare, and community development. Social sustainability addresses how social issues can be managed to ensure the organization's long-term survival (Mani et al. 2016). For shipping companies, the rationales of being socially responsible include improving employees' job satisfaction, customer loyalty, relationships with partners, community, and authorities, and financial performance (Fafaliou, Lekakou, & Theotokas, 2006). Furthermore, a socially responsible shipping company focuses on integrating economic, social, and environmental concerns and balancing between the need for operational efficiency, shareholder value, and attention to the interests of non-financial stakeholders (Parviainen, Lehikoinen, Kuikka, & Haapasaari, 2017; Poulovassilis & Meidanis, 2019). Social sustainability is essential in decision-making processes (Lee et al., 2019; Wagner, 2017). Both environmental and social responsibilities in the shipping industry are motivated by the need to comply with existing and possible future regulations. (Acciaro 2012; Parviainen et al. 2017).

1.3.3.1. Corporate Social Responsibility (CSR)

In maritime transport, CSR is defined as “the integration of social and environmental concerns in the business operations of shipping firms and the interaction with stakeholders voluntarily” (McWilliams et al. 2006; Pawlik et al. 2012; Poulovassilis and Meidanis 2019; Parviainen et al. 2017; Yuen et al. 2018). CSR activities include, for example, social reporting, prompt response to supplier complaints, prioritization of employees’ health and safety, monitoring of quality, the environmental impact of products and services (Fafaliou et al. 2006). Stakeholder involvement is a central CSR activity in which commercial stakeholders such as customers, suppliers, etc., are essential. Also, collaboration with non-financial stakeholders such as trade unions, local community organizations, etc., should be considered (Poulovassilis & Meidanis, 2019).

1.4. Maritime pollution and legislations

Transport activities are responsible for several adverse external effects (Sys et al. 2012), among which ships are emitting a range of gases from their operations at sea and in port areas. The emissions produced by navigation result from the combustion of fuel in internal combustion engines (Chang et al. 2014) and due to the energy used by ship engines - mainly HFO – (Doudnikoff & Lacoste, 2014; Pettit, Wells, Haider, & Abouarghoub, 2018) which are greenhouse gas (GHG), carbon dioxide (CO_2), volatile organic compounds (VOC), NO_X, SO_x, particulate matter (PM). CO_2 is the most significant GHG released by ships which is the main reason for global warming. Acid rain is caused by SO_x and NO_x, both highly undesirable due to their effects on human health (Serra & Fancello, 2020).

The adverse environmental effects of MarSC not only include air pollution but other types of marine pollutions consist of ballast water discharge; noise pollution; safety and security at the ports; hazardous substances; oil pollution; dust; residues; garbage; anti-fouling coatings; collisions, and physical disturbance (Corbett et al. 2009; EEA, 2009; Caric, 2016; Psaraftis, 2016; P. T. W. Lee et al. 2019) which result in poor air quality and negatively impacting on the health of local communities (Walker, 2016). There are different public and private regulators in the MarSC at local, national, and international levels, such as port authorities, local governments, European Union, and international organizations such as IMO, which are involved in adjusting relevant legislation to mitigate these detrimental effects. The regulations are not limited to maritime shipping only, covering port activities and hinterland transportation.

1.5. Sustainable Development Goals (SDGs)

Next to these International legislations, SDGs are scheduled as the great sustainability improvement plan worldwide. SDGs are a comprehensive agenda that stimulates economic, environmental, and social sustainability. In 2015, the United Nations (UN) released the document entitled 'Transforming our world: the 2030 agenda for sustainable development, in which 17 SDGs along with 169 targets were announced (Wang et al. 2020).

By definition, *"the 17 SDGs and their targets seek to realize the human rights of all and to achieve gender equality. They are integrated and indivisible and balance the three dimensions of sustainable development: the economic, social, and environmental. They explore to build on the Millennium Development Goals and complete what they did not achieve"* (United Nations, 2015)[1].

[1] For further info regarding the objectives and definition of each SDG, read United Nations (2015).

1.5.1. Sustainability trends in MarSC

The IAPH initiated a World Ports Sustainability Program (WPSP) in May 2017. The program, guided by the UN's 17 Sustainable Development Goals, aims to improve and organize future port sustainability efforts worldwide and develop international cooperation with supply chain partners. WPSP is created along with five themes: i) resilient infrastructure; ii) climate and energy; iii) community outreach and port-city dialogue; iv) safety and security; and v) governance and ethics. Table 1.2 gives data on the interest area and the number of port projects per category.

Table 1. 2: WPSP aspects and projects

WPSP theme	Main focus areas	2018	2019	Total
Resilient infrastructure	Anticipating, both physically and digitally, the demands of maritime transport and landside logistics, IT assisted optimization of port operations; IT assisted optimization of the supply chain	7	31	38 (21%)
Climate and energy	Initiatives to reduce GHG emissions from ships and increase the efficiency of port operations	15	28	43 (24%)
Community outreach and port-city dialogue	Initiatives dealing with environmental externalities such as air and water pollution, noise, waste, initiatives addressing societal needs and demands, e.g., recreation, green spaces, education, culture, heritage, and local economy	24	44	68 (38%)
Safety and security	Health and safety emergency preparedness and response, port area security, and cybersecurity	3	8	11 (6%)
Governance and ethics	CSR initiatives, sustainability policy, planning and reporting	8	11	19 (11%)
Total		**57**	**122**	**179**

The Table shows that the number of projects filed in all categories has increased significantly. In total, 179 port projects have been submitted in which the community and port-city category received the most significant attention by addressing roughly two-fifths of all projects; climate and energy are next, followed by resilient infrastructure. The number of projects focusing on governance, ethics, safety, and security is lower.

With 72 entries, European port projects are the most well-represented geographically, followed by Asia (32), America (22), Oceania (15), and Africa (1). Some ports have several projects submitted, while others collaborate on initiatives involving multiple ports from other continents.

1.6. Objectives, Research Questions, and Methodology applied

Even though shipping is widely known for its overall environmentally friendly performance compared to road and air transport, it remains characterized by several undesirable environmental impacts (Serra & Fancello, 2020). MarSC sustainability is a broad topic, and different stakeholders and regulatory agencies are involved in mitigating a large number of environmental and social threats to human health and the ecosystem; however, according to the EU Maritime Transport (2021), the five top environmental impacts derived from maritime shipping are greenhouse gas emissions, air pollution, underwater noise, non-indigenous species, and oil pollution. In this Ph.D., air pollution (SO_x) and the spread of non-native species are addressed from an economic perspective based on available environmental regulations derived from IMO.

Moreover, the MarSC sustainability's main gaps are realized based on the conducted comprehensive literature review. Table 1.3 plots these issues and the current regulators and suggests solutions for each obstacle applied in this doctoral thesis.

Table 1. 3: Problems, regulations, and suggested solutions per Ph.D. chapter

Existing gap and environmental impact	External powers and regulators	The proposed solution for filling the gap
BWM and its exceptions have mainly been discussed from an ecological perspective	Marine Environmental Protection Committee (MEPC)	The cost-benefit analysis of possible exemptions of the BWM, the possibility of setting up a so-called Same Risk Area (SRA) (Chapter 4)
Less attention has been paid to the impacts of green practices and emission regulation on the shippers	International Convention for the Prevention of Pollution from Ships (MARPOL)	An economic evaluation of three alternative technologies, i.e., MDO, LNG, and Scrubber system, both from ship owner and cargo owner perspectives for two maritime trade routes, Asia-EU and the US-EU (Chapter 5)
The increase in illicit trafficking in European ports	Belgium Customs – Stroomplan[2] (2017)	Assessment of the feasibility of enhancing the supervision of the maritime container supply chain from an economic perspective for the port of Antwerp by developing a new cost calculation model (Chapter 6)
Supply chain analysis for containerized dry and reefer cargo	Shipping line and shipper	Port and supply chain analysis for transporting containerized reefer and dry cargo on the maritime round trade route from West Africa to Europe (Chapter 7)

Thus, four main applications are investigated in this thesis that is linked to MarSC sustainability. Each chapter includes a combination of two or all three dimensions of the sustainability of the MarSC that are also related to the UN SDGs.

[2] The plan is designed to bring together public and private actors to deal with the issue in an integrated and integral way (Easton 2020, Sys & Vanelslander 2020).

Table 1. 4: Relationship of sustainability aspects and SDGs with each chapter of Ph.D.

Sustainability aspect / Chapter	Economic (profit)	Environmental (planet)	Social (people)	Sustainable Development Goals
Chapter 4 (Ballast water and SRA installation)	✓	✓	✓	SDG 12 SDG 14
Chapter 5 (Alternative technologies to mitigate sulfur emissions)	✓	✓	✓	SDG 9
Chapter 6 (Enhancing the supervision of containerized cargo)	✓	-	✓	SDG 16
Chapter 7 (Supply chain analysis in terms of dry and reefer cargo)	✓	✓	-	SDG 9

Maritime economics is the primary sustainability dimension investigated in all the chapters, while the environmental regulations and social issues are the main drivers of this Ph.D. In other words, the planet and people are the extraneous powers for the economic assessment of sustainability practices. The common line between four application studies can be classified into three primary groups:

MarSC-related:

This Ph.D. covers different segments and stages of the MarSC, including hinterland transport, seawaters, maritime shipping, and port and terminal operations to improve the sustainability of the MarSC at regional, national, and global levels. Notably, chapter four is about the shipping transport within neighboring countries, ports, and coastal areas, while chapters five and six investigate the deep sea and intercontinental maritime shipping and port operations from East Asia and the US to Europe. Also, chapter seven considers the whole supply chain from an origin point in Africa to a European destination by considering ocean shipping and terminal operation. Figure 1.3 plots a general overview of the ties of Ph.D. chapters with the MarSC segments and main actors in each chapter.

Sustainability-related:

The economic dimension is the primary aspect assessed in each chapter as the thesis targets maritime economics. In addition, environmental and social aspects are considered indirectly in some chapters based on the determined purposes. This Ph.D. acknowledges the environmental regulations and social perspectives as the complementary and external levers to fulfill the economic assessment. Particularly, chapters four and five address all three aspects of sustainability, namely the environmental, economic, and social dimensions. While chapter six encompasses economic and social perspectives, the economic and environmental dimensions are considered in chapter seven.

SDG-related:

All the SDGs can be effective in maritime shipping and in the port industry; however, those with the ambitions of reduction of pollution and waste, growth of trained and skilled employees, protection of marine and coastal ecosystems, and adaption of green technologies are more related to the purposes of this doctoral thesis. Therefore, this Ph.D. pertains to four critical UN SDGs, namely:
SDG 9 is defined as '*adoption of clean and environmentally-sound technologies to upgrade infrastructure and retrofit industries to make them sustainable'* and addressed in chapters five and seven.

SDG 12 is related to *'achieving the environmental management of chemicals and all wastes and minimizing their adverse impacts on human health and the environment'* investigated in chapter four.

SDG 14 pertains to '*protecting marine and coastal ecosystems'* and is considered in chapter four.

SDG 16 is about '*reducing illicit financial and arms flows and combat all forms of organized crime,'* considered in chapter six.

The main objective of this Ph.D. is to provide the economic assessment of the most selected and promising technologies and methodologies to overcome the negative impacts of the marine shipping and port industry and bridge the available shortcomings. Besides, it will enhance the sustainability of maritime shipping in terms of economic, environmental, and social perspectives concerning the current International Conventions and legislations and by considering the possible opportunities.

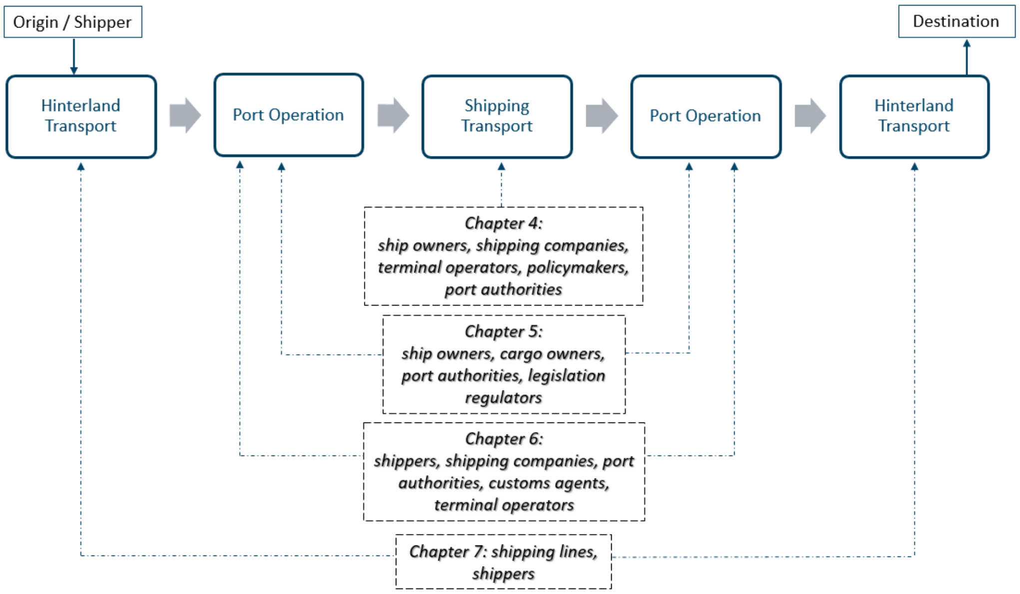
The main overarching research question is:

What is the economic impact of sustainability issues on maritime shipping in various trade routes from different stakeholders' standpoints?

To respond to this primary research question and to obtain the objective of this Ph.D., several sub-research questions are addressed, which are investigated through chapters four until seven. This Ph.D. thesis is based on an application approach, and each application study is researched in an independent chapter.

Although the vessel owners and shippers are the main stakeholders considered in this Ph.D., the perspectives of other actors are widely investigated: who are the problem owners of sub-research questions and are also the main beneficial parties of the outcomes of each application study.

Figure 1. 3: The common line of Ph.D. chapters with different segments of MarSC and the actors involved in each chapter



The thesis is organized into eight chapters, and several ports are investigated throughout the research; however, Port of Antwerp is regarded as the primary application in this Ph.D. as it plays an essential role in the data collection and calculation process. The following sections illustrate each application briefly by addressing each chapter's objective, research questions, and applied methodologies.

1.6.1. Chapter 4: Economic impact analysis of installing an SRA under the Ballast Water Management Convention (BWMC)

Regarding shipping and maritime transport, the research done in chapter 4 is related to increasing the sustainability of the MarSC from environmental and economic perspectives by studying the implementation of the BWM Convention for all ships. Ballast Water affects the marine environment and causes ecological, economic, and human health problems. By transferring the sediments, harmful organisms, and invasive species to a new area, next to adverse impacts on local biodiversity and extinction of existing native species (Sensorex, 2021), there is a high risk of detrimental consequences on human health (Takahashi et al. 2008). Chemical exposure from BWMS is a potential threat for the ship's crew, port state inspectors, and the general public. Non-occupational exposure scenarios also include the consumption of seafood from ballast water discharge areas (Werschkun et al. 2014).

The BWM and its exceptions have been approached mainly from an ecological perspective in the literature. Thus, it is vital to look at the convention from an economic perspective. To do so, chapter four concentrates on the economic analysis of possible exemptions of the BWM, in particular the possibility of setting up a so-called SRA.

The methodology of this chapter can be applied extensively around the world. As an application study in chapter four, the economic effects of establishing an SRA within Belgium and the Netherlands are analyzed.

In chapter four, two main research questions are addressed in detail.

- *What is the cost and benefit of installing an SRA between neighboring countries, Belgium and the Netherlands, from vessel owners' standpoint?*

- *Which criteria should be investigated for selecting SRA in terms of vessel types?*

To estimate the ballast water discharge volume for different types of vessels, a broad literature review is performed together with requesting the required data from the authorities of all the ports involved in the research, namely port of Antwerp, Port of Zeebrugge, Port of Oostende, Port of Rotterdam and Zeeland Seaports. Consequently, the evaluation of the economic impacts and the total net benefit of installing an SRA is obtained.

In this chapter, the data collection method is desk research and inquiring the data from the authorities of the ports included in the study. Then, a novel typology of vessel types that can be considered in the SRA is developed based on yearly BW consumption and previous port of call of vessels. The applied methodology is the cost and benefit calculation of the ships based on the obtained typology leading to the total net benefit of installing the SRA.

1.6.2. Chapter 5: Economic evaluation of alternative technologies to mitigate sulfur emissions in maritime container transport from both the vessel owner and shipper perspective

SO_x is harmful to human health, causing respiratory symptoms and lung disease. They can lead to acid rain, harming crops, forests, aquatic species, and ocean acidification (IMO, 2020c, UNCTAD 2020). Due to the increasing attention concerning the emission reduction legislations of maritime shipping, chapter five assesses the economic impact of alternative fuels/technologies to comply with the regulations on maritime shipping and especially in the current ECAs, both from ship owner and cargo owner perspectives for two maritime trade routes Asia-EU and the US-EU respectively. The main objective of this chapter is to evaluate economically three promising alternative technologies, i.e., Marine Diesel Oil (MDO), Liquefied Natural Gas (LNG), and Scrubber system, to mitigate the sulfur emissions in existing ECA zones caused by maritime shipping. The following research questions are addressed in this chapter:

- *What are the maritime costs for the selected alternative options from a vessel owner's point of view?*

- *What is the effect of these technologies on the generalized chain cost, hence from shippers' standpoint?*

In this chapter, the data of the input parameters are obtained by the desk research based on literature review and online searching. Consequently, the existing Chain Cost Model (CCM) is adjusted and updated to achieve the goals of this chapter.

1.6.3. Chapter 6: The feasibility and potential of enhancing the supervision of maritime container supply chain from an economic perspective

Ensuring the safety and security of maritime shipping and minimizing the risks and the potential losses is an issue of great importance (Chang et al. 2014). In 2016, approximately 70 tonnes of cocaine were seized in European ports (European Monitoring Centre for Drugs and Drug Addiction, 2018).
Regarding the sustainability of ports in the MarSC, the fulfilled research in chapter six is to increase the security of the supply chain at the port of Antwerp by enhancing the supervision of import cargo which aims at reducing illicit trafficking and leads to improvement and enhancement of the economic and social aspects of the MarSC. The import and transit of narcotics via the port of Antwerp are increasing, as are the associated social problems in and around the city (Easton 2020; Sys and Vanelslander 2020).

In this research, the cost and benefit of *maximizing the scanning* of containerized cargo at the terminal and port levels have been assessed, and the possibility of it without hampering the logistics chain has been evaluated. The following research questions are addressed in this chapter:

- *What is the total cost of scanning the containers for the actors involved under various scanning rates at the terminal level?*

- *How will the total supply chain cost change under the increasing scanning rate for some specific maritime routes to Europe?*

For this research, as the scope of the study is comprehensive and includes different sectors of the maritime chain, several interviews are conducted to gather the data with relevant stakeholders in the MarSC such as shippers, shipping companies, freight forwarders, trucking companies, terminal operators, customs agents, etc.
In the second stage, a new cost calculation model is developed to evaluate the total scanning cost experienced by stakeholders under varying scanning rate scenarios. Last but not least, the updated version of the CCM is employed to compute the generalized chain cost.

1.6.4. Chapter 7: Supply chain analysis and economic assessment of the transportation of dry and reefer cargo in the West-Africa-Europe trade route

Port selection criteria have been under attention by academia in the last decade and have a vital role in the MarSC. This issue confirms that the effect of port choice analysis should not be neglected to improve the sustainability of MarSC. In addition, the port selection process becomes more challenging and sensitive if the market is for perishable goods such as fruits and vegetables.

Chapter seven identifies and analyzes the best port of call among three Antwerp, Rotterdam, and Flushing ports for transporting containerized reefer and dry cargo on the maritime trade route from West Africa to Europe. Furthermore, total marine cost (vessel owners' perspective) and the generalized chain cost (shippers' perspective) are evaluated for several pre-defined origin-destinations for the West Africa-Europe route and based on the (non)transshipment cargo types and the combination of different (un)loading ports in Europe, the UK, and other regions namely Baltic, Northern part of the North Sea, and Ireland.

There are two main research questions of chapter seven:

- *Which port among three West-European ports, i.e., Antwerp, Rotterdam, and Flushing, is the best option to be called at in the West-Africa-Europe route in terms of (un)loading cargo rate and the lowest maritime cost and supply chain cost?*

- *Considering more ports of call in the European leg of the chain to maximize the vessel's loading capacity, what would be the economic impact analysis on both vessel owner's and cargo owner's costs?*

In this chapter, the data of import/export container flow volumes for the ports in the West-Africa-Europe chain are gathered by the desk research based on online searching. Thereupon, to estimate the total maritime cost and the generalized chain cost, an updated version of the CCM is utilized to attain the purposes of this chapter.

1.7. Structure of the thesis

In this Ph.D., several methodologies will be applied to fulfill the objectives and respond to each chapter's research questions. After the introduction (problem statement) in each chapter, a comprehensive literature review is carried out to figure out the state of the art of the content. In the next step, the data collection approach is illustrated to obtain the required data and input parameters relevant to the research questions of the chapters.
The CCM is the primary model, and it calculates the generalized cost per TEU by considering the hinterland, port operation, and maritime shipping costs in a loop. The model requires origin-destination pairs in both hinterlands in the legs; hence a complete loop is defined. The main input parameters are the size of the hinterland area, a determined container loop, and a container vessel. However, CCM is confronted with some limitations, such as it applies only to containerized ships and does not support other types of vessels, and is mainly established to calculate the supply chain cost with some possibility to evaluate the total maritime cost.

In this Ph.D., CCM is mainly used to achieve the objectives and respond to the sub-research questions in chapters five and seven. However, for chapters four and six, as the purposes are beyond the scope of the CCM, two new methods are established to reply to the sub-research questions.

In chapter four, as the objective is to assess the economic impact of the possible establishment of an SRA by providing the cost and benefit estimation based on a developed typology of vessel types, it is needed to use a different methodology to fulfill the goal.

Moreover, in chapter six, a new model is developed to respond to the first sub-research question by considering many cost components and addressing different stakeholders' perspectives. Table 1.5 plots different applied methodologies based on each chapter's relevant objectives and research questions.

Table 1. 5: The structure of chapters four until seven in terms of the methodology applied

Chapter 3	The applied methodology
Chapter 4	Development of typology classification and cost-benefit calculation
Chapter 5	An update of the existing CCM
Chapter 6	An update of the existing CCM Development of scanning cost approach
Chapter 7	An update of the existing CCM

Chapter 2 illustrates the maritime shipping trends and the literature review of the design and framework of MarSC sustainability. Moreover, port industry and port sustainability are discussed explicitly with the definitions of sustainable and green ports.

Chapter 3 explains the primary applied methodology in this Ph.D.; the CCM. van Hassel et al. (2016a) developed the model which calculated the total maritime cost (vessel owner cost) and the generalized chain cost (cargo owner cost) by the possibility of the breakdown of the charge into the hinterland maritime and port sections. This chapter describes the concept of the model in detail with a general overview of the input parameter and data collection references of the model.

Chapters 4 and 5 cover all three aspects of MarSC sustainability, i.e., environmental, economic, and social dimensions. Chapter 4 depicts the SRA assessment under Ballast Water convention management between Belgium and the Netherlands. Chapter 5 applies an economic evaluation of alternative technologies to mitigate sulfur emissions in maritime container transport from the perspective of the vessel owner and shipper.

Chapter 6 includes the economic and social perspectives of MarSC sustainability. This chapter assesses the feasibility and potential of enhancing the supervision of the maritime container supply chain from an economic outlook for the port of Antwerp.

Economic and environmental dimensions of MarSC sustainability are considered in chapter 7. This chapter evaluates the effect of port choice on the total maritime cost and the supply chain cost.

Finally, chapter 8 explicates the conclusions of the thesis. Additionally, this chapter interprets the obtained lessons, implications on different stakeholders, faced limitations, and future research of this Ph.D.

Chapter 2: Literature Review

2.1. Introduction

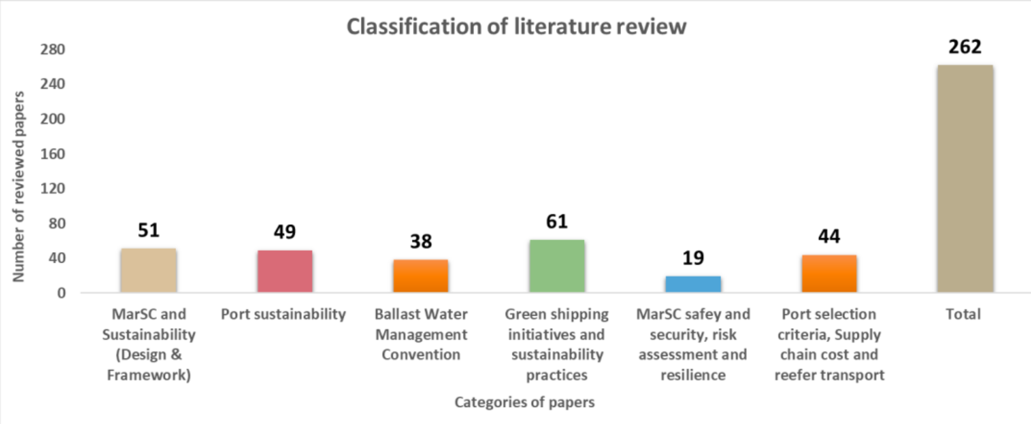
This chapter performs a literature review of the sustainability of MarSC and investigates the economic, environmental, and social aspects of the maritime shipping and port industry. It explains the significance of maritime shipping and the main points of maritime trade for different types of cargo.
This chapter analyzes numerous case studies worldwide and is spread over several countries from East Asia to North America. The objectives of this paper are threefold. Firstly, defining a sustainable and green MarSC targets marine shipping and port industry processes and stakeholders. Second, to have a comprehensive overview of the extant research and available technologies and measures on the sustainability dimensions of MarSC, and third, to figure out the literature gap in maritime shipping. As a consequence of this chapter, it is clear which subjects have captivated the interest of academics and industry and which fields still need to be explored further.

The methodology of accomplishing the ambitions of this paper includes three stages. In the first stage, various academic articles, book chapters, and conference proceedings were selected in which the journal papers were collected through Science Direct and Scopus as the leading databases of scientific research in the period between 2000 to 2020. The applied keywords were as follows: sustainable MarSC; social MarSC; sustainable shipping; maritime transport and logistics industry; environmental sustainability of maritime shipping; green shipping; economic sustainability of maritime shipping; sustainable port; port selection criteria; ballast water management convention; ballast water treatment system; ballast water exemption, and same risk area; dry and reefer cargo in marine shipping; supply chain cost; alternative fuels, and technologies in the MarSC; Emission Control Areas (ECAs); environmental regulations in the maritime industry; emission reduction measures; safety and security in the maritime sector, and resilience in MarSC.

Then, in the second stage and after scanning the abstract and keywords of the papers, 262 papers were selected and reviewed attentively and precisely with the focus on the objectives, methodology applied, previous studies, and obtained results and conclusion. In the third stage, the snowballing technique is used in which the reference list of all the peer-reviewed papers is investigated to detect supplementary articles on the subject.

The reviewed papers are categorized into several classes based on the common keywords and the objectives of the content. Figure 2.1 plots the classification of the literature review throughout the entire thesis.

Figure 2. 1: Various categories of reviewed papers



The analyzed papers are classified into six groups based on the keywords and objectives of each chapter of the Ph.D. thesis. This chapter will explain only the literature review of the first and second blocks: MarSC and sustainability (Design & Framework) and port sustainability issues. Chapter four discusses the reviewed literature of the BWMC, regulations, and exemptions, while chapter five represents the green shipping initiatives and research to mitigate maritime pollution and emission. Maritime risk assessment and safety and security challenges in MarSC are described in chapter six. Besides, the papers about the port choice criteria, supply chain cost, and inland and reefer transport are demonstrated in chapter seven.

Maritime shipping has attracted the scholars' attention more since 2010 as 229 papers were published from 2010 to 2020 compared to only 33 in the first decade of the 21st century. It shows the growing interest and importance of the topic in academic research.

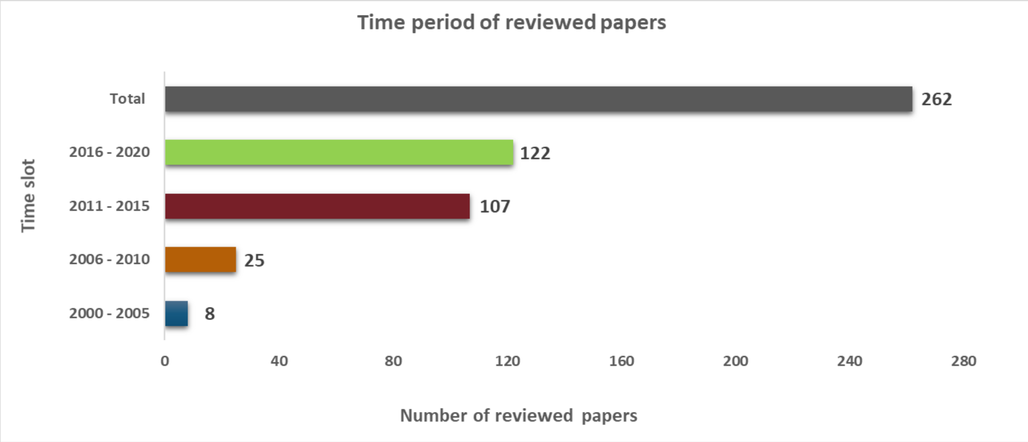
Several reasons can justify this issue. Firstly, there is a dramatic growth in handling cargo in maritime shipping. For example, handling containerized cargo has increased significantly in the last decade worldwide, starting from 543 million TEUs in 2010, reaching 811 million TEUs of containers in 2019.

Secondly, although this remarkable rise leads to economic growth in the industry, it causes several detrimental environmental and social impacts such as air and noise pollution, cargo operations, chemical, and waste management, oil spills, collisions at sea, etc. Consequently, several domestic and international regulatory organizations set new legislations or ratified the existing laws to mitigate these adverse consequences on the ecosystem, habitats, and human health, such as International Maritime Organization (IMO) and Sustainable Development Goals set by United Nations in 2015.

Relevant stakeholders such as shipping lines, vessel owners, and port authorities took the initiative to employ green technologies and sustainability practices in compliance with available regulations in which ports publish technical and statistical reports covering sustainability aspects and improvements in their supply chain process to improve the reputation and to better the competitiveness with other ports. Also, many researchers developed studies and methodologies in measuring the caused environmental pollutions of maritime shipping globally and evaluating the effectiveness of the applied green practices in the marine and port industry.

All these issues reveal the significance of sustainability of the MarSC for all the involved stakeholders and result in a significant number of published journal and conference papers, books, reports, and web page articles.

Figure 2. 2: Number of reviewed papers based on the published year



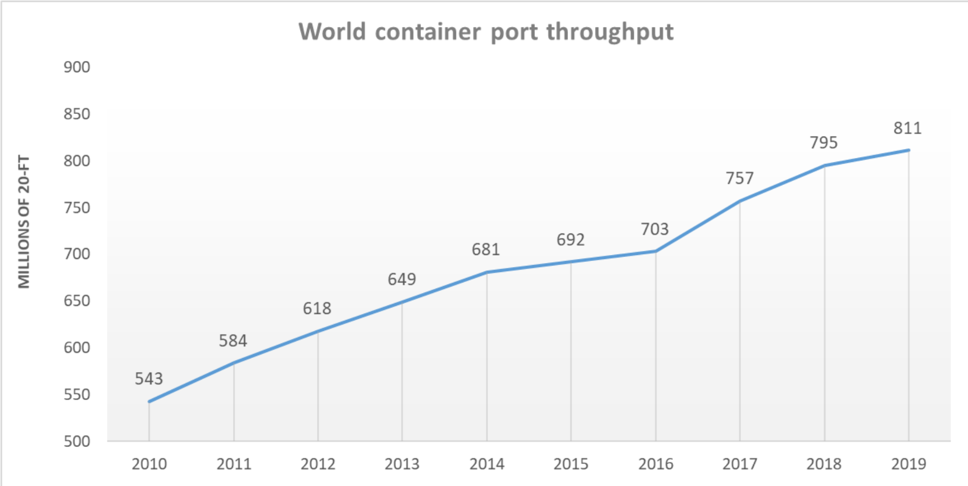
The findings of this chapter are relevant for all actors in the MarSC. The results provide an expanded road map that can be used to advance the sustainability of the MarSC and will be the basis for empirical work.

This chapter is organized in the following way. In section 2.2, the trends in maritime shipping are reported. Section 2.3 explains the environmental regulations to curb the negative impacts of marine shipping, port, and terminal operations, while section 2.4 presents the design and framework of MarSC sustainability. Section 2.5 addresses port sustainability and narrate the definition of green ports and extant research on port sustainability issues, and the last section, section 2.6, outlines the primary outcomes and conclusions of the conducted literature review in this doctoral thesis.

2.2. Maritime shipping trends

Global container demand grew at 6.4% in 2017 (UNCTAD, 2018). Furthermore, containerized cargo remained relatively the most dynamic segment of seaborne trade, rising 4.3% in 2018. Yet, its expansion slowed from 6.4% in 2017 (UNCTAD, 2019). Meanwhile, dry bulk commodities trade increased by 4%, up from 1.7% in 2016. Crude oil shipments rose by 2.4%, down from 4% in 2016, while, together, refined petroleum products and gas increased by an estimated 3.9% (UNCTAD, 2019). In 2019, 811 million TEUs of containers were handled in container ports worldwide, reflecting an additional 16 million TEUs over 2018. World container port throughput grew by 2% between 2018 and 2019 (UNCTAD, 2020). Figure 2.3 draws the container throughput worldwide since 2010.

Figure 2. 3: Throughput of the container ports in the world

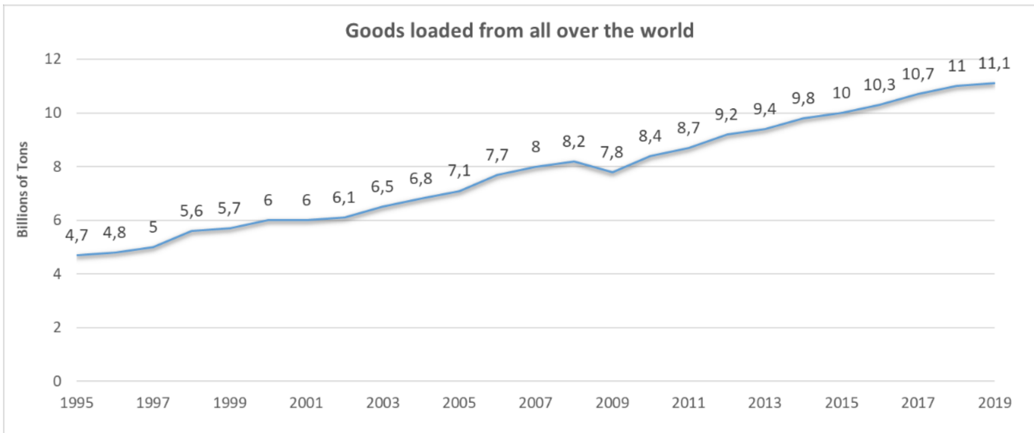


Source: https://stats.unctad.org/handbook/MaritimeTransport/Indicators

In 2019, nearly 65% of global port-container cargo handling was concentrated in Asia (the share of China alone exceeded 50%). Europe ranked second in terms of container port-handling volumes. Other regions in descending order are North America (7.7%), Latin America and the Caribbean (6.5%), Africa (4%), and Oceania (1.6%) (UNCTAD, 2020).

International maritime trade growth slowed in 2019, hitting its lowest level since the 2008–2009 global financial crisis. Maritime trade volumes expanded by 0.5%, down from 2.8% in 2018, and reached a total of 11.08 billion tons in 2019 (UNCTAD, 2020).

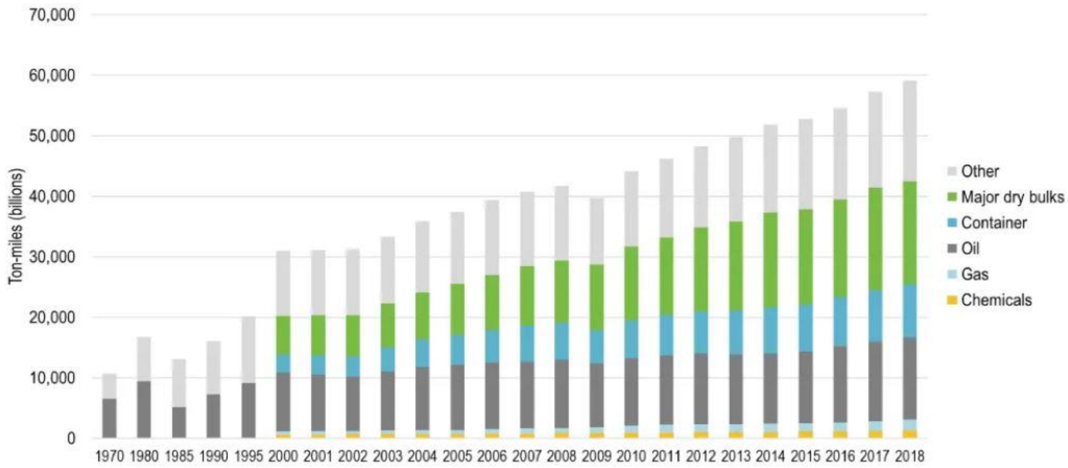
Figure 2. 4: Goods loaded worldwide



Source: Author's composition based on https://stats.unctad.org/handbook/MaritimeTransport/WorldSeaborneTrade

Dry cargo continued to account for over two-thirds of total maritime trade volumes, while liquid bulk commodities, including crude oil, refined petroleum products, gas, and chemicals, accounted for the remaining share. In 2019, growth in all market segments decelerated. Trade-in dry cargo expanded at 1.1% over 2018, and tanker trade volumes contracted by 1%.

Figure 2. 5: World seaborne trade by cargo type 1970 – 2018 [3]



Source: Transport geography (2021) based on UNCTAD Review of Maritime Transport, various years

In 2019, 55% of recorded port calls worldwide were passenger ships, followed by tankers and other wet bulk carriers (12%), container ships (11%), and general cargo break bulk ships (10%) (UNCTAD, 2020).

However, the COVID 19 crisis led to fewer port calls for most vessel types during the first half of 2020. Regarding the container ship port calls, the number of arrivals started to fall below 2019 levels about mid-March 2020 and began to recover gradually about the third week of June. By mid-June, the average number of container vessels arriving weekly at ports worldwide had sunk to 8,722, an 8.5% year-on-year drop. Since then, the average weekly calls started to recover, rising to 9,265 in early August 2020 (UNCTAD, 2020).

2.3. Environmental regulations in the MarSC

Relevant regulations have been considered under the auspices of the IMO, including a set of technical and operational measures to reduce emissions from international shipping (UNCTAD, 2011; UNCTAD, 2012). International maritime policies and regulations are mainly set by the United Nations' IMO and enter into force by nation-states (Parviainen et al. 2017).

Several initiatives have been carried out regarding safety and pollution in the shipping industry, namely the International Convention for the Safety of Life at Sea (SOLAS), MARPOL for the International Convention for the Prevention of Pollution From Ships (in which MARPOL 73/78 is an environmental convention to prevent marine water quality pollution and marine air pollution that may occur because of ships (Lee & Nam, 2017) and the Convention on the International Regulations for Preventing Collisions at Sea (COLREG), the International Safety Management Code (ISM Code), the International Ship and Port Facility Security (ISPS Code), the Standards of Training, Certification and Watch keeping for Seafarers (STCW), Customs and Trade Partnership against Terrorism (C-TPAT),

[3] Major dry bulks are iron ore, grain, and coal.

customs inspections in international ports (Container Security Initiative – CSI), the Convention on Oil Pollution Preparedness, Response and Co-operation regarding Hazardous and Noxious Substances (OPRC-HNS), the Anti fouling Systems (AFS) Convention, the BWM Convention, and the Ship Recycling Convention are key regulations aiming at raising environmentally and socially responsible behavior of companies in the industry (IMO, 2010, IMO, 2012; Barnes and Oloruntoba 2005; Lu et al. 2009; Chang et al. 2014; T. Lee and Nam 2017; Parviainen et al. 2017). Furthermore, the Convention for the Control of Harmful Anti-fouling Systems on Ships, 2001 defines anti-fouling systems as 'a coating, paint, surface treatment, surface or device used on a ship to control or prevent unwanted organisms' (UNCTAD, 2020).

The IMO and the governments of other countries have formulated related emission regulations to control air pollution. Currently, four significant regulations: Annex VI of maritime agreement regarding oil pollution (MARPOL) 73/78 Convention, European Union (EU) law, Environmental protection agency (EPA), and California air resources board (CARB) regulation are utilized typically (Deng et al. 2021).

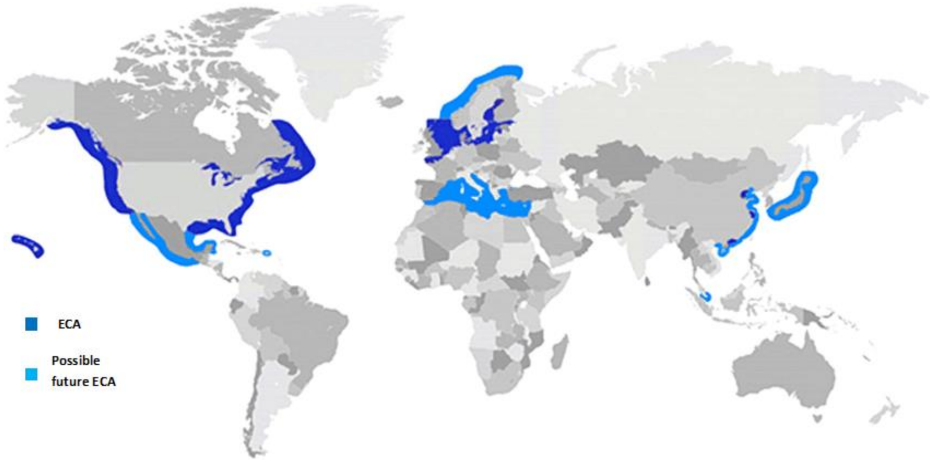
As mentioned above, the environmental regulations of a MarSC are not confined only to the reduction of GHG emission and air pollution of SO_x and NO_x; they cover broader aspects such as BWM, the safety of life as sea and security at ports, oil spills prevention, and preparedness regulations such as SPCC Rule [4]. Furthermore, plastic pollution is seen as a global problem that needs urgent action. IMO has agreed on a comprehensive action plan with all measures intended to be completed by 2025. Also, underwater noise is driven by the concern that ship noise may negatively impact a broad range of sea life. IMO guidance was issued in 2014, and some countries have been particularly active in engaging in studies (Nyhus, 2020). The following sections explain the MARPOL Annex VI and BWM Convention as two principal environmental regulations considered in this Ph.D.

In 2008, the Marine Environment Protection Committee (MEPC) of the IMO adopted amendments to the MARPOL Annex VI entitled "Regulations for the Prevention of Air Pollution from Ships," which limits the emission of SO_x NO_x and volatile organic compounds (VOCs). These amendments set the **global limit** on the sulfur content of a ship's fuel to 3.50% (35,000 ppm) (effective 1 January 2012), followed by a reduction to 0.50% (5,000 ppm) (effective 1 January 2020) (MARPOL Annex VI, 2005; IMO 2008; Psaraftis and Kontovas 2010; Wang, 2014; Cullinane and Bergqvist 2014; Fagerholt and Psaraftis 2015; IMO, 2016; T. Lee and Nam 2017).

Within ECAs,[5] in which more stringent controls on SO_x emissions apply, the sulfur content of fuel oil must be no more than 0.1% (1000 ppm) from January 1st, 2015 (Doudnikoff & Lacoste, 2014; Lindstad & Eskeland, 2016). ECA targets pollutant air emissions, such as SO_x and NO_x, and has set no standard for GHG emissions (Walker, 2016). Four ECAs have also been defined by MARPOL. The first two sulfur Oxide ECAs were established in Europe, in the Baltic Sea and the North Sea, and took effect in 2006 and 2007, respectively; the third was established in North America and took effect in 2012; and the fourth was established in the United States Caribbean Sea, covering waters adjacent to the coasts of Puerto Rico and the United States Virgin Islands, and took effect in 2014. The North American and US Caribbean ECAs also regulate NO_x emissions (Fagerholt & Psaraftis 2015; UNCTAD, 2018). The current and possible future US, European, and Asian ECA zones are plotted in Figure 2.6.

[4] Spill Prevention, Control and Countermeasure (SPCC) Rule. Visit www.epa.gov for further info.
[5] ECAs are sea areas in which stricter controls are established to minimize airborne emissions from ships as defined by Annex VI of the 1997 MARPOL Protocol.

Figure 2. 6: Current and possible future ECAs



Source: http://www.kolbia.org (Kolbia, 2019)

Asia holds the most top-ranking ports and contains the most densely populated major coastal areas globally. However, no countries and regions in Asia have yet designated the ECAs (Chang et al. 2014). According to GARD (2018), in September 2015, China released a five-year program that aims to reduce SO_x and NO_x emissions by designating the Pearl River and Yangtze River Deltas and the Bohai Rim Waters as ECA's place a cap on the sulfur content of fuel oil in the ECA's at 0.50% including eleven major ports.

Panagakos et al. 2014 investigate the impact of a possible designation of the Mediterranean Sea as a SECA on the transport of consolidated cargoes between Greece and Germany. The results predict that this designation will cause a modal shift in favor of the road-only route. However, the environmental implications of the resulting modal choices are positive with all emissions examined. Sys et al. (2016) mention the reasons for the absence of an ECA in the Mediterranean as a politically unstable climate, legal disputes, and negative tendencies spilling over from the North.

Undoubtedly, Ships' Ballast Water (BW) is the most crucial mechanism transporting exotic marine and freshwater organisms worldwide, and the transport of invasive species in the BW of ships threatens marine ecosystems globally (Verna & Harris, 2016). Besides, invasive species, such as aquatic animals, plants, and algae, can attach themselves to the outside of ships (ship hulls), known as biofouling (UNCTAD, 2020).

The International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention) was adopted in February 2004 by the IMO (IMO 2004; Jee & Lee 2017; Rey 2018). The BWM Convention was ratified and entered into force on September 8th, 2017. In the BWM Convention, ships must have onboard and implement an approved BWM Plan. Ships must maintain a Ballast Water Record Book to record when ballast water is taken on board, circulated, or treated for BWM purposes and discharged into the sea (IMO, 2004). Besides, a set of 15 guidelines regarding BW exchange, sampling, treatment systems, risk assessments, and management plan provides technical guidance to support the implementation of the convention's principles (Cheng, Liu, Olenin, & Su, 2019). The BWM Convention aims to prevent the risk of the introduction and proliferation of non-native species following the discharge of untreated ballast water from ships. It is considered one of the four most significant threats to the world's oceans and a substantial threat to biodiversity (UNCTAD, 2011; UNCTAD, 2015; UNCTAD, 2020).

Also, several countries have taken the approach to nationally implement BWM requirements, of which some have also ratified the BWM Convention. Most of these requirements are based upon the IMO Ballast Water Exchange (BWE) Standard (Regulation D -1), some countries refer to the Ballast Water Performance Standard (D-2 standard), and a minority addresses land-based BW reception facilities (David and Gollasch 2015).

2.4. Design & Framework of sustainable MarSC

Lam (2015) investigates to design a sustainable MarSC by focusing on customer requirements (CR). The author defines four customer requirements for a sustainable MarSC, namely (i) cost- and price-competitiveness, (ii) pollution reduction, (iii) efficient use of fuel and resources, and (iv) health, safety, and security.

Table 2. 1: Customer requirements for a sustainable MarSC

Customer requirements	Sustainability Aspect
Cost- and Price-Competitive (CR1)	Economic aspect (cost-efficiency)
Pollution Reduction (CR2)	Environmental and social aspects (including air and water pollution and benefits people's health and living conditions)
Efficient Use of Fuel and Resources (CR3)	Environmental and economic aspects (saving cost)
Health, Safety, and Security (CR4)	Social aspect

Source: Authors' composition based on Lam, 2015

The customer requirement of pollution reduction is to be met mainly from the technology and engineering aspects rather than the business aspects of working with stakeholders in the supply chain, including shippers and seaports. Based on Lam, 2015, in terms of relative importance, the essential CRs are CR1 and CR4, while CR2 and CR3 are ranked in relatively lower priority. Eight design requirements (DRs) are identified for container shipping lines to design a sustainable MarSC to meet these customer requirements. Table 2.2 shows the ranking of each DR with its relevant CRs.

Table 2. 2: Design and customer requirements for a sustainable MarSC

Ranking of DRS – Top to down	Satisfied Customer Requirements
DR5 - Use of Green Design Ships, Engines, and Machinery	Pollution Reduction (CR2) and Health, Safety and Security requirements of the customer (CR4)
DR1 - Integrated Supply Chain Workflow	Cost and Price Competitive (CR1) and Health, Safety, and Security requirements of the customer (CR4)
DR4 - Optimal Routing and Scheduling	CR1 and CR3
DR6 - Use of Low-Sulfur Fuel and Renewable Energy	Pollution Reduction (CR2)
DR3 - Cooperation with Seaports and Terminals	-
DR8 - Preventive Measures for Accidents	Pollution Reduction (CR2) and Health, Safety and Security requirements of the customer (CR4)
DR7 - Ballast Water Treatment and Residue/Waste Control	Pollution Reduction (CR2)

DR2 - Cooperation with Shippers	-

Source: Authors' composition based on Lam, 2015

Based on the above Table, it is observed that no single design requirement can adequately address all of the customers' needs. Wagner (2017) defines the concept of the triple bottom line related to sustainability which states the necessity to act and make a profit taking into account the three dimensions at the same time, which means that a result of a company activity should not measure only a financial gain but also environmental and social performance of the corporation. Lee et al. (2019) confirm that sustainability is imperative to minimize economic and social costs, reduce environmental impacts caused by such ship operations, and improve residents' health. Ren and Lützen (2017) consider technological and political dimensions besides the three pillars in a sustainability assessment.

Kum Fai Yuen et al. 2017 analyze the drivers of sustainable shipping. The results reveal that: (i) stakeholder pressure, (ii) shipping companies' attitude, and (iii) behavioral control towards practicing sustainability are the preconditions of sustainable shipping practices. Kum Fai Yuen et al. 2019 analyze the effects of sustainable shipping capabilities on business performance. It is found that shipping companies can pursue the development of sustainable shipping capabilities on two fronts: (1) sustainable exploitation capability or (2) sustainable exploration capability. Tran et al. 2020 identify that critical success factors (CSFs) of sustainable shipping management (SSM) in descending order of their importance are (1) stakeholders' focus, (2) intra-firm management, (3) new technology acceptance, (4) inter-firm collaboration, and (5) strategic fit

Wang et al. 2020 reveal that the core responsibilities of the maritime sector lie in the plans concerning the provision of four SDGs, namely (i) SDG 8: Safe and healthy working environment,(ii) SDG 9: Development of green technologies and transport infrastructure, (iii) SDG 12: Responsible waste management and ship recycling, and (iv) SDG 14: Proper BWM and coastal ecosystem protection.

From the shippers' perspective, CSR can improve their satisfaction with the services of the appointed shipping firm (Yuen et al. 2016a). CSR initiatives aim to move towards environmentally and socially responsible and safe shipping industry practices (Parviainen et al. 2017). CSR has received renewed attention from shipping firms to complement their classical competitive strategies (Yuen et al. 2017). Fafaliou et al. 2006 investigate the initiatives and related benefits of applying CSR in the European maritime sector. The results are demonstrated in Table 2.3.

Table 2. 3: CSR – Measures and Benefits

CSR application	CSR initiatives, benefits, and barriers
Initiatives relevant to the CSR concept	Health and Safety - Codes of conduct - Friendly environmental activities - Better community relations - Socially responsible investments - Company's participation in affairs of public interest and human rights - Life-long learning - Activities in support of deprived groups or ethnic minorities - Charity giving - Better relations with customers
Benefits from CSR initiatives	Improvement of employees job satisfaction - Improvement of customers royalty - Advantages related to the satisfaction of companies' owners - Raise of productivity - Improvement of partners-investors relations
Reasons for not implementing CSR initiatives	Lack of public support or encouragement - Lack of information for the implementation – No self-consciousness of CSR impacts business activity.

Source: Authors' composition based on Fafaliou et al. (2006)

Weber (2008) categorizes the main business benefits associated with the implementation of CSR into monetary and non-monetary fields and summarizes in five classes such as (i) positive effects on company reputation; (ii) positive effects on employee motivation, retention, and recruitment (iii) cost savings (iv) revenue increases from market share (v) risk mitigation management. On the other hand, Lu et al. (2009) discover that three dimensions of CSR are (i) community involvement and environment, (ii) disclosure, and (iii) employee and consumer interests. Also, there is a positive relationship between CSR dimensions and financial performance in the container shipping industry. Poulovassilis and Meidanis (2019) define the potential CSR challenges for shipping companies and relevant benefits for maritime shipping.

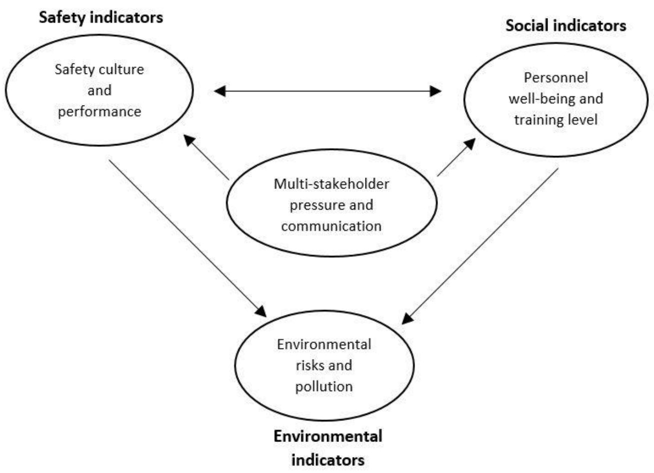
Table 2. 4: CSR challenges

Potential CSR challenges for shipping companies		Benefits of CSR
Environmental	Consideration of the overall impacts of Climate Change (Carbon Reduction and Energy Efficiency), Emissions to Air, Discharges to water, Waste Management, Recycling.	Protection of the environment
Social	Consideration of the employee relations, cultural diversity, job attractiveness, creation and retention, training and development, safety, and security.	Safety promotion and risk prevention
Economic	The balance between the overall business environment and stakeholder revenue and profits with the overall global economic outlook and the worldwide supply/demand situation.	Profitability Cost efficiency

Source: Authors' composition based on Poulovassilis and Meidanis 2019

Parviainen et al. (2017) examine the potential of multi-stakeholder alliances between both the primary stakeholders (financial) and secondary stakeholders (non-financial) to promote CSR in the shipping sector in terms of safety as well as environmental and social responsibility by proposing a comprehensive approach to measure the CSR in the shipping industry.

Figure 2. 7: Holistic indicator approach to define and measure the CSR in the shipping industry



Source: Authors' composition based on Parviainen et al. 2017

Based on the results, multi-stakeholder pressure based on primary and secondary stakeholder actions promotes the adoption, implementation, and enforcement of CSR practices in the shipping industry to push towards improved regulations (Parviainen et al. 2017). In addition, there is a robust positive association between CSR and enterprise value shipping (Syriopoulos et al. 2020).

Jasmi and Fernando (2018) determine maritime green supply chain management (MGSCM) as the integration of environmental initiatives and innovations among the MarSC that includes internal and external organizational units (ports, shipping companies, etc.) and partners to support value-added activities for materials flow (container, bulk, and general cargoes). The concept of implementing green shipping practices in MarSC requires internal functional coordination within the shipping company and external integration with shippers and consignees in the physical cargo movement process (Lam, 2015). Implementation of green operations strengthens the environmental and social performance of shipping firms' commitments to satisfy customer expectations (Liao, Lu, & Tseng, 2011; Venus Lun et al. 2015). Green supply chain management can assist the maritime sector in complying with IMO regulation and achieving sustainability goals that benefit society and future generations (Jasmi & Fernando, 2018). Lirn, Lin, and Shang (2014) find three decisive dimensions of green shipping management capability: greener policy, greener ships, and greener suppliers.

Table 2. 5: Dimensions of green shipping management

Primary factors of green shipping management	Definition
Greener policy	It is concerned with implementing an environmental policy to create a vision or culture of environmental protection (K. Lai et al. 2011).
Greener ships	It focuses on preventing air pollution [i.e., CO_2, SO_X, NO_X, and PM] from ships, improving ships' BWM methods (BSR 2010; The A.P. Moller-Maersk Group 2011).
Greener suppliers	It includes guiding suppliers to establish their environmental programs, requiring suppliers to provide testing certification for green product conformance, pressuring suppliers to take environmental action.

Source: Authors' composition based on Lirn et al. 2014

There are three functions of MGSCM, which are (i) to achieve customer needs while at the same time improving profitability and competitiveness, (ii) to conform with regulations, and (iii) to control social and environmental impacts (Cheng et al. 2015). The use of green technology in ship operations can directly influence the pollution generated, fuel, resource usage, and health and safety levels (Lam, 2015). Regulations, social needs, and market changes are among other reasons that lie beyond the strategies of individual organizations for implementing green initiatives (Caniëls et al. 2016).

Jasmi and Fernando (2018) investigate the relationship between drivers of green MarSC management (i.e., top management, regulation, green initiative, and security) and dimensions of MGSCM practices. The main dimensions of MGSCM are monetary flow, information flow, integration practice, customer needs, and conformity to regulations.

2.5. Port industry and port sustainability

Ports are considered critical nodes of global trade and supply chains, which have a complex organizational structure (Kang & Kim, 2017; Sanchez Rodrigues et al. 2015) and contribute to economic development as well as employment opportunities (Lam et al. 2013; Sakalayen et al. 2017; Hou and Geerlings, 2016; Ashrafi et al. 2019) that facilitate the movement of goods and cargo Harrald et al. (2004) as a connection point linking the maritime mode to the hinterland (both the local regions and inland transportation) by an intermodal transport network (Harrald et al. 2004; Barnes and Oloruntoba 2005; Lam et al. 2013; Wan et al. 2016). Moreover, ports can promote corporate sustainability through cleaner production initiatives and other proactive approaches such as resource efficiency, optimization of logistical networks, enhancing safety and security in a port, etc. (Kim & Chiang, 2014). Ports can actively contribute to the sustainability of maritime transport by taking a more significant role and responsibility towards society and the environment (Klopott, 2013).

While having numerous positive external effects, ports are also major energy consumers and sources of pollution (Chen et al. 2019) and are responsible for negative environmental and social impacts deriving from activities such as dredging, anchoring, cargo handling, marine fuel bunkering, waste management, and cargo operations (Dinwoodie et al. 2012; Klopott, 2013; Walker et al. 2019; Ashrafi et al. 2019; Garg and Kashav 2019). The main seaport stakeholders are classified into four main groups by Notteboom and Winkelmans (2001) and are defined as any individual or group of persons holding a legitimate interest or being affected by port action or inaction (Notteboom, Parola, Satta, & Penco, 2015; Notteboom & Winkelmans, 2001).

Table 2. 6: Stakeholders in the port industry

Group of stakeholders	Stakeholders
Internal stakeholders	Port authority, employees, unions, shareholders, board members
External stakeholders	Transport operators (ship-owners, railway companies, trucking companies), terminal operators, forwarding agencies, shipping agencies, industrial companies
Community stakeholders	Community groups, civil society organizations, the press
Legislation and public policy stakeholders	Countries and world organizations

Source: Authors' composition based on Notteboom and Winkelmans (2001)

Besides the above stakeholders, government and logistics service providers are within the same value-driven chain of port stakeholders (Lam, 2011; Lam et al. 2013). Port authorities are responsible for strategic seaport planning (Dooms, Verbeke, & Haezendonck, 2013).

2.5.1. Sustainable and green ports

Green ports maintain a good balance between environmental impact and economic benefit (Chen et al. 2019) by engaging in the proactive development, implementation, and monitoring of practices at local, regional, and global levels beyond regulatory compliance (Acciaro, 2015).
The sustainable port concept requires port authorities to account for economic, environmental, and societal considerations in their strategy definition, in line with the triple bottom line approach (Elkington 1997; Henriques and Richardson 2004; Acciaro 2015). The operation of ports depends on supporting infrastructure and human capital and the ability to continue to perform under disruptions from incidents (Asadabadi & Miller-Hooks, 2020). Infrastructure investment, cost, efficiency, service quality (Lam et al. 2013), collaboration among the stakeholders, and governance for environmental performance are crucial for sustainable port operations (Kang & Kim, 2017; Lam et al. 2013).

2.5.2. Recent research on the port's sustainability

Port sustainability and development have received remarkable attention from stakeholders in maritime shipping and have been investigated by numerous scholars. In this paper, 49 papers are reviewed, focusing on reducing the environmental impact of port operations, improving economic benefits, and increasing social welfare. The most significant findings and results regarding port operations are discussed as follows.

Acciaro et al. (2014) list the main green strategic objectives, namely landlord function, regulatory function; operator function; and community manager, enabling reviewing the port authority's main procedures and investigating the influence of environmental sustainability on them. Kim and Chiang (2014) identify the goals of sustainability practices in port operations in three various aspects, namely (i) economic (container traffic growth); (ii) social-environmental (low environmental impacts and corporately responsible image-making), and (iii) operational (operational efficiency improvement).

Similar research has been done by Kang and Kim (2017) to generate a structure consisting of five sub-dimensions conceptualizing sustainability practices in port operations: environmental technologies, monitoring and upgrading, process and quality improvement, communication and cooperation, and active participation. Asgari et al. (2015) examine the sustainability performance of five major UK ports from environmental and economic perspectives. In Table 2.7, the critical criteria to measure sustainable performance in UK ports are plotted.

Table 2. 7: Criteria and sub-criteria to measure sustainability in UK ports

Dimension	Criteria / Sub-criteria
Economic aspect	Cost-efficiency. Transportation cost; Fuel cost; Electricity cost; the shipping cost
	High quality of services. Port congestion; Loading and unloading cost; Infrastructure; Service and waiting time
Environmental aspect	Establish environmental policies
	Identify environmental impacts
	Environmental objectives and priorities
	Environmental dimension
	Commitment identification

	Training and awareness. All staff are educated and trained about sustainability
	Emergency preparedness and response. To minimize damages to the environment and environmental risk management

Source: Authors' composition based on Asgari et al. 2015

Wagner (2017) defines sustainability in the ports as employment, environmental issues, air emissions, fair working conditions, equal opportunities, occupational health and safety, education, training, and skills development. Schipper, Vreugdenhil, and de Jong (2017) present a method for interpreting and comparing sustainability in long-term port and port-city plans for a diverse set of ports (size, type, geographic location). Oh, Lee, and Seo (2018) demonstrate that the economic issue associated with offering employment opportunities is the most crucial measure for sustainability assessment of seaports, followed by environmental concerns and social factors. Interestingly, CS implemented in port strategies and operations could help improve ports' relationships with its diversified stakeholders, including government, policymakers, and customers (Ashrafi et al. 2019). Vanelslander et al. (2019) investigate the maritime and port industry innovation, showing that dominant aspects are multi-dimensional innovation, including technological, managerial, organizational, and cultural aspects.

Tichavska and Tovar 2015 suggest eco-efficiency indicators as a practical tool to measure performance within the context of ports in which external costs are combined with port operations profiles to estimate the eco-efficiency performance. Sislian et al. 2016 reveal that various environmental indicators of port sustainability are (i) noise pollution, (ii) air quality, and (iii) dredging operations and disposal.

Ports can intervene in two main ways to improve the environmental performance of maritime transport beyond their organizational and physical boundaries: by lowering tool implementation complexity through more vital collaboration within global value chains; and by enhancing emission visibility through alliances with cargo owners and regulators Poulsen et al. 2018. Ballini et al. 2020 identify the port's sustainable measures and provide a framework including the economic, social, and environmental dimensions, contributing to United Nations Sustainable Development Goals (SDGs). Lu et al. 2020 investigate sustainable development in container terminals (Hong Kong) and its impact on stakeholders' retentions. Results indicate that social aspects concerning "employee job security and safety" and "terminal traffic accidents prevention" are the top most essential attributes among sustainability assessment criteria, followed by economic measures of "ensuring cargo handled safely and effectively," "offering employment opportunities" and "facilitating to economic activities."

Other significant references and research on the port sustainability content are plotted in Table 2.8, targeting the main objectives and case studies.

Table 2. 8: Research on port sustainability

Reference	Objectives and Case Study
C. C. Chang and Wang 2012	To reduce pollutants in port areas. Port of Kaohsiung (Taiwan)
Park and Yeo 2012	To evaluate the greenness of a seaport. Korean ports (Incheon, Busan, Gwangyang, Pyeongtaek, and Ulsan)
Dooms et al. 2013	To analyze the role of path dependency in the socio-political process of long-term strategic port planning. Port of Antwerp

Parola et al. 2013	To analyze the content of disclosure in port authorities. Top 125 container ports in the world
Acciaro et al. 2014	To investigate the environmental sustainability of the seaports. Port innovation initiatives in the Ports of Genoa, Antwerp, Rijeka Singapore, Zeebrugge, Los Angeles/Long Beach, Hamburg
Kim and Chiang 2014	To investigate sustainability practice in port operations. Port of Busan
Acciaro 2015	To represent the relationship between CR and competitiveness in the port sector
Notteboom et al. 2015	To provide stakeholder management principles in the port domain. Port of Rotterdam
Sanchez Rodrigues et al. 2015	To examine sustainability issues for maritime operations by assessing total CO_2 emissions. UK ports
Halim et al. 2016	To present a quantitative model for port-hinterland freight distribution systems. European port-hinterland
D. P. Song et al. 2016	To analyze the port competition problem involving hinterland shipments and transshipment cargoes. Southampton and Liverpool ports (UK)
H. Chen et al. 2017	To apply the concept of resilience to the context of a port-hinterland container transportation network. Port of Gothenburg
Kang and Kim 2017	To conceptualize the structure of sustainability practices in international port operations. Shanghai, Hong Kong, and Busan ports
Knatz 2017	To examine the effects of competition in governance and strategic decision-making. US ports
Min-Ho Ha et al. 2017	To develop a Port Performance Measurement framework. Four Korean container ports
Pallis and Vaggelas 2017	To discuss the evolution of the container ports market. Greek ports
Wagner 2017	To identify the most critical sustainability aspects for port authorities and other port stakeholders. Selected European ports
K. H. T. Wong et al. 2017	To assess the involvement of the port industry. Port of Hong Kong
C.N. Wang et al. 2018	To improve the competitiveness of the Vietnamese port logistics industry. Vietnamese ports
Guo et al. 2018	To propose a port resource integration and cooperative operation method in multi-port regions. Ports in Northeast China
Linder 2018	To analyze the success of the Vessel Speed Reduction (VSR) Program to improve air quality. Ports of Los Angeles and Long Beach
Oh et al. 2018	To evaluate the decisive criteria for the port sustainability assessment. Ports in South Korea
Z. Song et al. 2018	To study the cooperation mode between ports and liner companies in the case of competition between heterogeneous ports. Shenzhen and Nansha ports (China)
W. Wang et al. 2018	To investigate Green Project Planning (GPP) of ports to minimize the total costs and maximize the total emission reduction.
Yang et al. 2018	To discover the risks posed by climate change on ports. Container ports in Hong Kong, Taiwan, and Mainland China
Ashrafi et al. 2019	To assess the current state of Corporate Sustainability through surveying port managing companies and authorities. Canada and the US
Hossain et al. 2019	To assess the state of Canadian ports sustainability initiatives and Green Marine Environmental Program (GMEP's). Canadian ports

X. Lai et al. 2019	To examine the incentives of forecast information sharing from the port and the effect of the carrier's risk behavior on sustainability investment decisions in a MarSC.
Lam and Yap 2019	To review existing sustainability frameworks and conduct a stakeholder analysis for sustainable development of the port city. Port cities Guangzhou and Shenzhen
Monios 2019	To identify the critical issues in the port governance
Asadabadi and Hooks 2020	To study port reliability and resilience and the importance of ports in supporting a larger resilient maritime system. Southeast Asia centroid, Singapore, Port Klang, Jakarta, Belawan, Europe centroid
Cong et al. 2020	To investigate the interaction between port production performance and the city's socio-economic development. Chinese ports
Munim 2020	To combine a qualitative and quantitative data analysis to investigate the association between technical efficiency and port service level of high technically efficient ports and terminals. Seventeen ports in twelve Asian countries
Narasimha et al. 2020	To identify and analyze crucial dimensions, port performance indicators, and key performance indicators for assessing the sustainability performance of ports. Liquid cargo based Indian major seaports
Senarak 2020	To understand the role of port's digitalization and adoption of environment-friendly technology in improving the container port's capacity, energy efficiency, and sustainability.

Source: Authors' composition based on all the references of the table

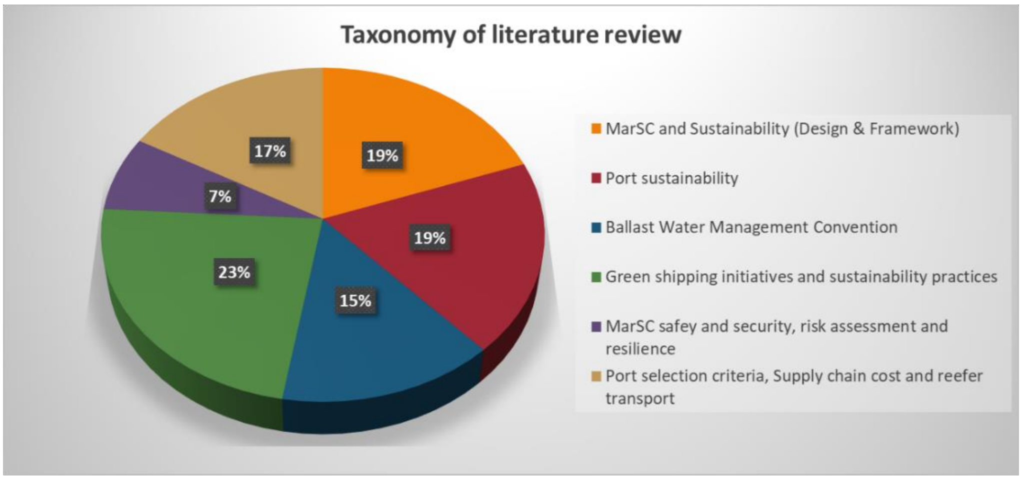
As can be seen from the above Table, the sustainability enhancement in the port sector has been assessed in various ports around the world. Due to these efforts, several methodologies have been developed, and topics such as port governance, stakeholder management, port competition, and emission reduction have been investigated.

2.6. Overall Observations

With the fast development of container transportation, MarSC has become one of the largest complex networks in the world (Liu et al. 2018). Efficient information flow and integration between maritime players are necessary to manage complex MarSC (Jasmi & Fernando, 2018). In the supply chain dimension, shipping companies have to coordinate cargo, information, and financial flows along the chain interfacing with various parties such as shippers and ports (Lam, 2015) and are responsible for the operation of ships concerning safety and environmental protection to provide long-term benefits (Poulovassilis & Meidanis, 2019) and produce services to satisfy the derived demand for the transport of cargoes on regularly scheduled service routes (Fafaliou et al. 2006; Lu et al. 2009). Other stakeholders involved in maritime shipping are shipyards, non-governmental organizations (NGOs), environmental organizations, repair yards, recycling industries, research and development organizations (Psaraftis, 2016), customs and regulatory authorities, which are involved both in the transport of goods and in information exchange (Davydenko, Zhang, & Tavasszy, 2014; Veenstra et al. 2008).

The sustainability of MarSC has been under attention by academia and industry in the last decade, and various research has been carried out in this field. In this chapter, 262 papers for twenty years between 2000-2020 have been reviewed precisely. Based on the literature, the majority of the essays in the field of MarSC belong to the assessment of environmental sustainability and emission reduction, while the research regarding merely the economic and social dimensions of MarSC is scarce. According to the literature review conducted, the maritime industry has adopted green strategies to improve resource efficiency and competitiveness in the industry. Importantly, legislations, social needs, and market changes are among other reasons that are mentioned to encourage individual organizations to implement green initiatives.

Figure 2. 8: Taxonomy of literature review



This chapter confirms that, although considerable research has been devoted to the economic and environmental assessment of MarSC sustainability from shipowner or shipping lines perspectives, less attention has been paid to the impacts of green practices and emission regulation on the shippers or cargo owners. This lack of research can lead to non-efficient policy-making decisions at the industry level when applying innovative and green technologies to mitigate maritime pollution. This Ph.D. attempts to overcome this barrier by considering the shipper's perspective.

It is observed that Ballast Water affects the marine climate, causing ecology, economics, and human health issues. However, the BWM and its exceptions have mainly been discussed from an ecological perspective in the literature. As a result, it is vital to consider the convention from an economic standpoint.

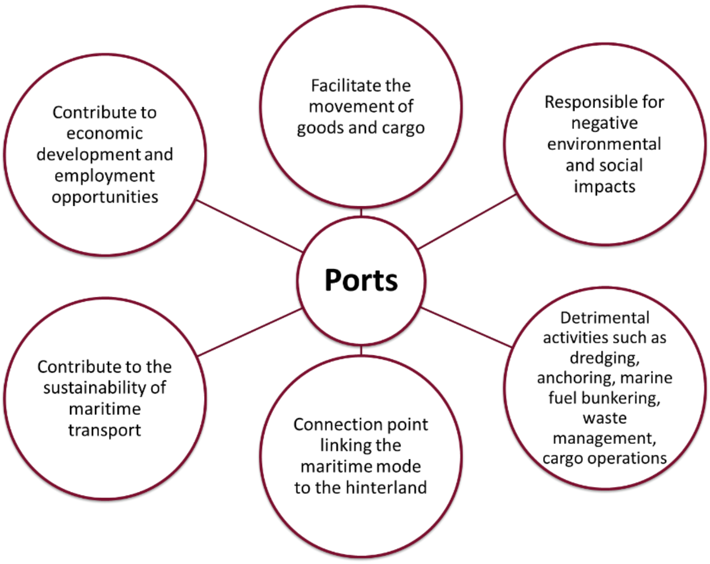
From an economic point of view, it appears that the cost-efficiency of maritime shipping is imperative to establish economic sustainability and maximize profitability. Besides, one of the critical drivers for shipping firms to adopt green operations is *performance*, which comprises both economic and environmental dimensions.

Maritime safety and security were researched by addressing the risk factors, risk mitigation challenges, regulations, and measures. Previous research has demonstrated that safety and security establishment in MarSC are among the most significant interest and major concerns as maritime shipping is subject to several types of risks grouped as internal, external, and supply chain risks in which the top risk factors belong to operational risks, cyber and terroristic attacks.

Regrettably, little research has described the social dimension of MarSC sustainability merely, and this aspect is scrutinized with a combination of economic and environmental aspects. Social sustainability improves the employees' job satisfaction and customer services, leading to the maritime stakeholders' economic and environmental performances. Due to the digitalization development of marine shipping, knowledge sharing, data processing and analysis, teamwork, and solid communicational skills are essential proficiency requirements. Furthermore, the supervision of the container supply chain needs to be enhanced to increase safety and security and to minimize the risk of illicit trafficking at the same time.

Notably, this chapter has confirmed that the ports are an essential part of sustainability developments, and it requires assessing the sustainability of ports to make optimal decisions and choose sustainable development strategies concerning MarSC. Besides, maritime authorities play a critical role in protecting society from the harmful effects of marine and port operations. Figure 2.9 summarizes the functions of the ports in maritime shipping.

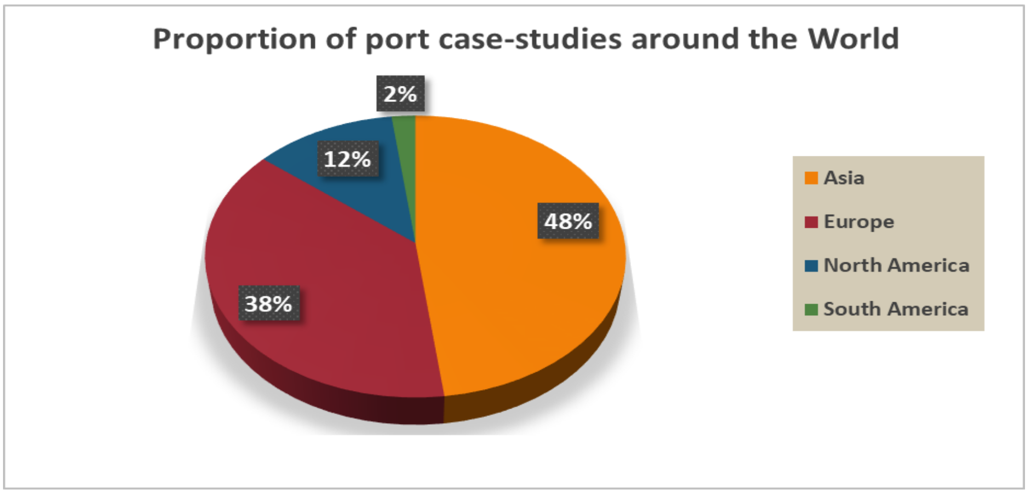
Figure 2. 9: Ports' influences on maritime shipping



As observed, various ports are investigated as case studies worldwide. However, most studies belong to the sustainability assessment of ports, including economic, environmental, and social dimensions, mainly in Asian and European ports, respectively. The most crucial objective is to improve port sustainability and consider the collaboration between port stakeholders and policymakers.

Sys and Vanelslander (2020) state that each stakeholder needs to control its MarSC (reduce uncertainty) and create value for every actor involved in the sustainable ecosystem to serve their customers better to manage the end-to-end integration of MarSC processes. Each player in the MarSC is engaged in multi-jurisdictional and multi-layered activities impacted by international, regional, national, and local governments and international private bodies (Lister, 2015). Furthermore, these players are concerned with the design, production, ownership, construction, administration, crewing of maritime trader vessels, training, classification, investment, finance liability, and insurance of shipping operations (Jasmi & Fernando, 2018). The responsibility and objectives of each stakeholder are necessary for taking action to reduce maritime emissions (Schwartz, Gustafsson, & Spohr, 2020).

Figure 2. 10: Ratio of ports on sustainability at the worldwide level (based on the selection of papers in the literature review)



Several application studies have been taken into account in this Ph.D. to cover the observed gaps in the literature review, which includes different dimensions of sustainability. The environmental, economic, and social dimensions of sustainability are described in chapters four and five. Chapter six examines the economic and social aspects, while chapter seven discusses the economic and environmental dimensions.

The contribution of this chapter to the literature is gathering a comprehensive overview of recent research, green initiatives, and technologies in MarSC, both in maritime shipping and in the port sector. Besides, this study is beneficial for relevant stakeholders in the MarSC and specifically for scholars by generating valuable scientific and theoretical implications. It has addressed the critical topics in the maritime industry and provided an extensive summary of previous research. To overcome the mentioned gaps in the literature and address the environmental regulations and social issues, chapter four assesses the cost-benefit analysis of potential BWM exceptions and examines the concept of establishing an SRA from an economic perspective. In chapter five, a cost comparison of three potential technologies, namely MDO, LNG, and the Scrubber system, is taken into account from the viewpoint of ship owners and cargo owners for two maritime trade routes, Asia-EU and US-EU.

Chapter 6 is about assessing the feasibility of improving the supervision of the maritime container supply chain from an economic perspective for the port of Antwerp by developing a new cost calculation model. Moreover, port and supply chain analysis of transporting containerized reefer and dry goods over the maritime round trade route from West Africa to Europe is the purpose of chapter seven.

Chapter 3: Applied Methodology - Overview of Chain Cost Model

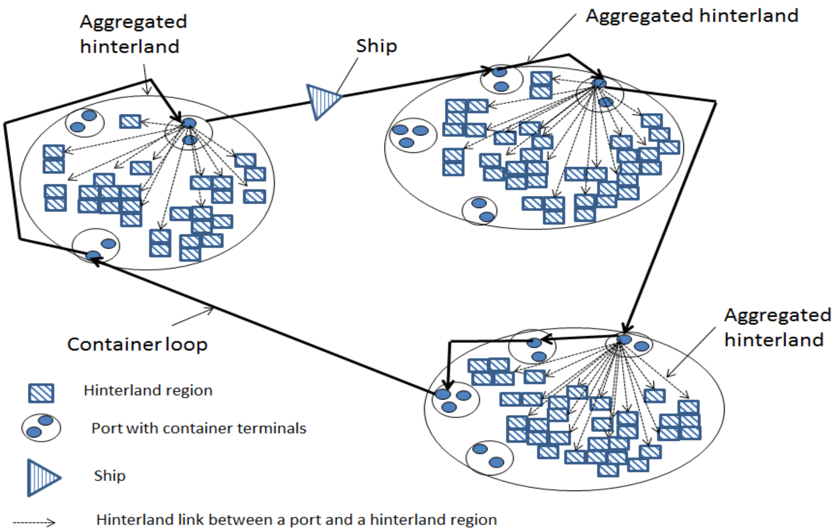
In this Ph.D., several methodologies are applied to fulfill the objectives of each chapter, specifically which were explained in the introduction chapter (see chapter 1). The main applied methodology is the CCM developed by van Hassel et al. (van Hassel et al. 2016a, 2016b[6]). In this chapter, the objective and a general overview of the model are described in detail. The goals of this chapter are first to explain the different parts of the model and how different sections are interrelated, and also, the process of calculating the generalized chain cost and its various cost components is demonstrated precisely.

Furthermore, the model is adapted for each chapter of the thesis where the CCM is applicable (chapters 5, 6, and 7) and based on each chapter's unique addressed research questions. The updates to the model will be explained separately in those chapters where some necessary changes are needed, and input parameters and adaptions to the base model are made.

3.1. Purpose of the CCM

The purpose of the CCM [7] is to calculate the generalized chain cost per TEU from a selected point of origin (i) in the hinterland (A), via a predefined container loop, to a destination point (j) in another hinterland (B) (van Hassel et al. 2016a, 2016b). In CCM, several terms need to be determined: hinterland area, aggregated hinterland, logistics chain, characteristics of ports and terminals involved, and hinterland connections (van Hassel et al. 2016a, 2016b). Figure 3.1 plots the concept of the CCM.

Figure 3. 1: General Concept of Cost Chain Model



Source: van Hassel et al. 2016a, 2016b

[6] Read these two papers for further information regarding the model.
[7] The model is coded in C# and uses Microsoft Excel (data) and JMP11 (maps) as output formats.

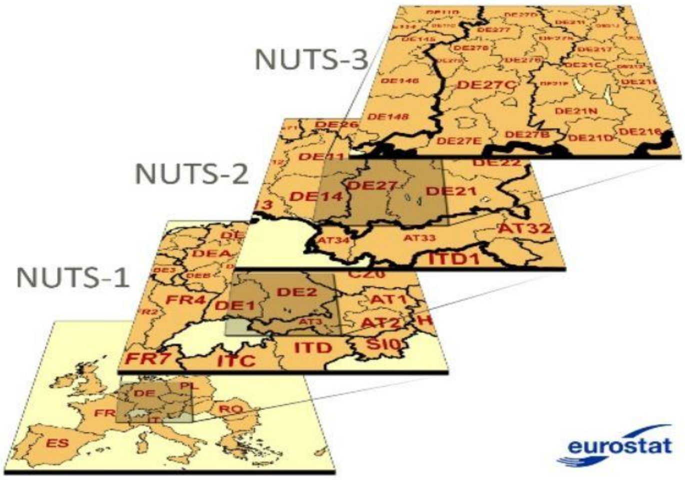
A logistics chain consists of a starting point and ending point and is determined as a route from a specific hinterland region (i) to another hinterland region (j). A logistics chain holds three significant legs: maritime shipping, port process, and hinterland transportation. As shown from Figure 3.1, in CCM, different aggregated hinterlands are connected via a route (container loop) and ports (bold lines). The container loop encompasses the maritime leg of the supply chain.

The aggregated hinterlands are defined as a summation of different smaller geographical areas, which in Europe correspond to NUTS-2 regions. Each aggregated hinterland is served by at least one or several ports (van Hassel et al. 2016a). The NUTS classification (Nomenclature of Territorial Units for Statistics) is a hierarchical system for categorizing the economic territory of the EU for three main objectives: (i) The collection and harmonization of European regional statistics (ii) Socio-economic analyses of the regions, and (iii) Framing of EU regional policies (Eurostat, 2020). Based on the NUTS classification (Eurostat, 2020), there are three central regions with different characteristics in terms of size, geography, and policy perspective, namely

- NUTS 1: including major socio-economic regions
- NUTS 2: including basic regions for the application of regional policies
- NUTS 3: including small regions for specific diagnoses

Figure 3.2 shows a generic overview of the NUTS regions in Europe.

Figure 3. 2: NUTS regions in Europe



Source: https://ec.europa.eu/eurostat/web/nuts/background

The NUTS 2016 classification considers 104 regions for NUTS 1, 281 areas for NUTS 2, and 1348 regions for NUTS 3 (Eurostat, 2020). Regarding ports characteristics, each port entails one or several terminals, and each terminal has specific features such as infrastructure elements like the maximum draft, terminal equipment like the number of container cranes, stacking cranes on the terminal, etc. From each port terminal, the hinterland connections via road, rail, and inland waterways (if applicable) to all the disaggregated hinterland regions are synthesized into the model, and the distances are determined from each terminal in the ports located in the aggregated hinterland to the different hinterland areas (van Hassel et al. 2016a).

In the CCM, eight aggregated hinterland areas are developed around the world, namely, the EU (from each terminal to 240 NUTS-2 regions), the UK (40 NUTS-2 regions), the USA (48 states), Brazil (65 regions), Australia (10 states), Western Africa (20 regions), Southern Cone (50 regions), and China (30 regions).

All the possible chains are estimated in the aggregated *to* the hinterland, meaning that the port cost and hinterland cost from the ports that are part of the loop and located in the aggregated *to* the hinterland are computed to all the hinterland areas (All NUTS-2 region in Europe). As all the combinations can be assessed, therefore, there is a feasibility to obtain the lowest chain cost from a port of origin to all the various hinterland regions showing among all the options, which ships, sailing routes, ports of call, and hinterland modes to be selected (van Hassel et al. 2016a).

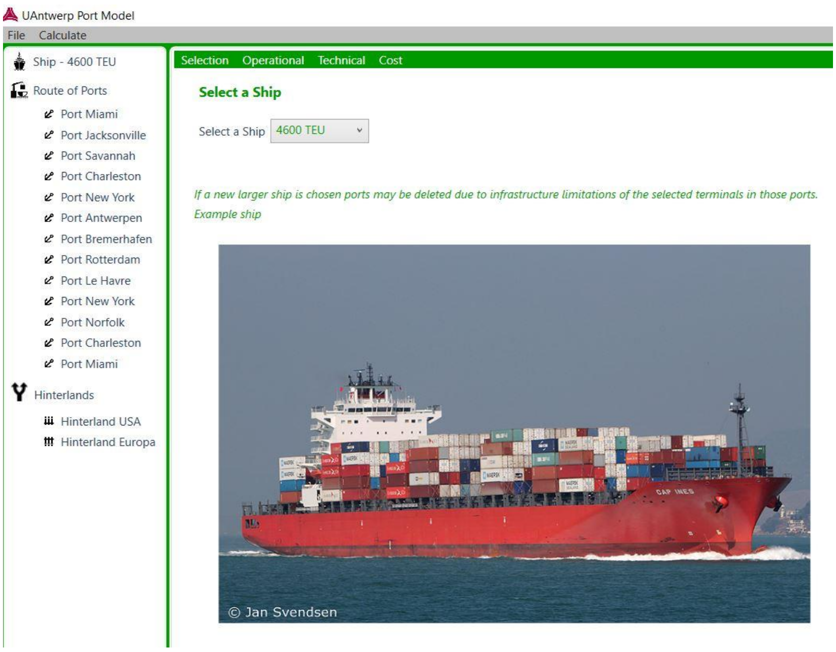
3.2. Input Parameters

There are four input elements for CCM, namely the selection of (i) a container loop, (ii) a vessel, (iii) the size of the aggregated hinterland, and (iv) the value of the cargo transported in the containers, which will be discussed in detail in this section.

3.2.1. Container loop:

The first input is the selection of a container loop. Several loops are developed in the model, namely Asia-EU, US-EU, South America – EU, and Africa – EU. Other maritime routes can also be created. Based on a database of different ports, it is possible to build a desired container loop. Furthermore, by applying the real data from the websites of the container lines, an actual loop can be combined in the model. Figure 3.3 draws the general overview of the US-EU route with all the ports involved for the vessel size 4,600 TEU.

Figure 3. 3: Ports in US-EU route for the vessel size 4,600 TEU

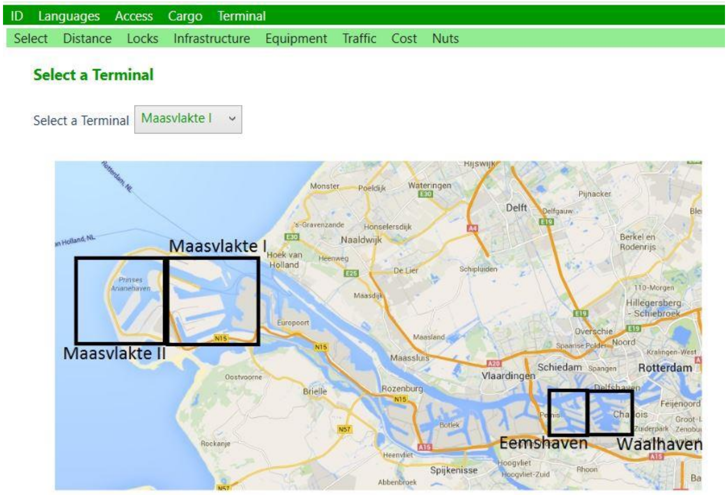


There are plenty of considered ports in each loop. The features of each port are defined based on the accurate data, such as maximum allowable draft port [m], rate of cargo loading, and unloading in the terminal [%]. It is possible to have the cargo division of transshipment, IWT, rail, and road for loading and unloading cargo.

3.2.1.1. Terminal Selection

In this part, one of the main sub-input parameters is the terminal selection. All the available terminals in each port in the selected loop are characterized in the model, choosing the required terminal.

Figure 3. 4: Terminals of Port of Rotterdam



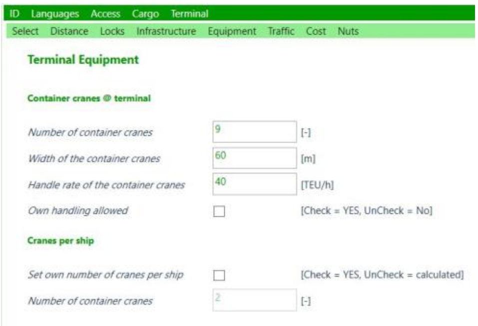
Based on the selected terminal, all the relevant data are pre-defined and can be modified such as:

I. *Infrastructure (maximum draft of the terminal [m], length of the terminal [m]), and if any locks should be passed to reach the terminal.*
II. *Terminal equipment (container cranes at the terminal (number, handling rate [TEU/h]), straddle carriers and stacking cranes at the terminal, etc.)*
III. *Traffic data (yearly turnover in TEU, average % loaded and unloaded)*
IV. *Cost Calculation: the detailed cost calculation of port dues, tug boats, pilotage, mooring, and unmooring costs, container handling costs[8] (terminal handling charges [EUR/container] and terminal operating cost [EUR/container]), and shifting cost (based on the number of shifts at the terminal).*

[8] The process of handling a container vessel at a port is modelled as different queues, using queueing theory. Therefore, based on the actual throughput of a port, the total handling time and cost can be calculated.

Figure 3. 5: Infrastructure properties of a terminal

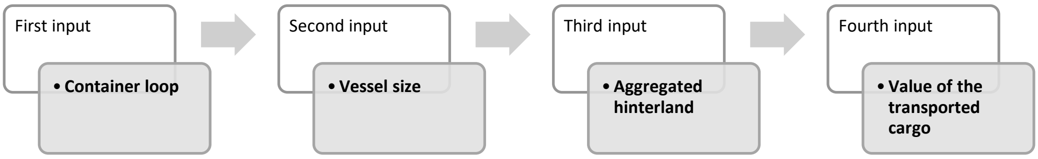
Figure 3. 6: Types of equipment of a terminal



Several sources are considered to obtain the values for the mentioned input parameters, such as Drewry (2005), which was mainly used for the ship's cost, while all the port and terminal-related costs are obtained via the websites of ports and terminals.

After choosing the desired container loop, the second input element is the selection of a vessel[9]. The third input parameter is the choice of the size of the aggregated hinterland, and the fourth input component is the value of the cargo transported in the containers.

Figure 3. 7: Input elements of CCM



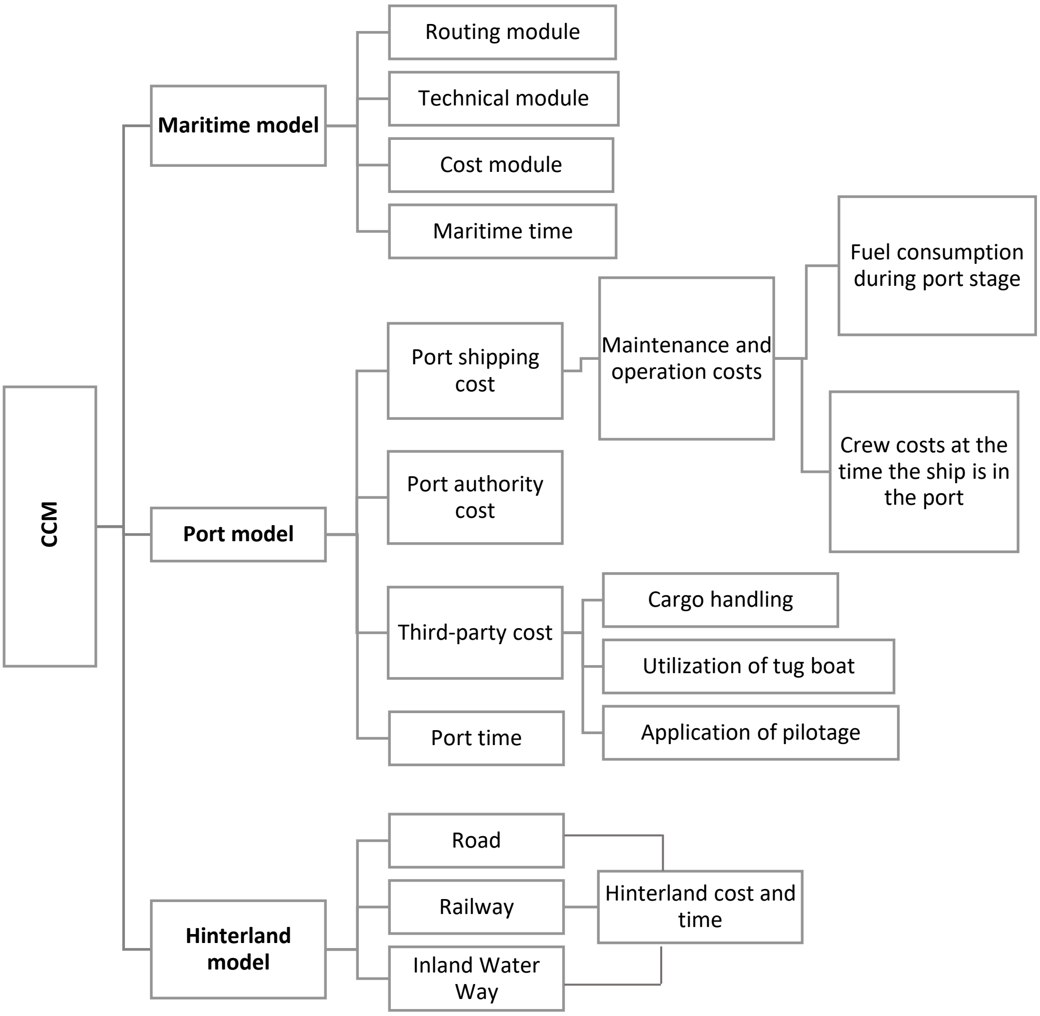
Source: Author composition based on van Hassel et al. 2016a

[9] In each loop, it might be the case that by choosing a larger ship, some ports might have to be removed from the loop. The reason is explained by the infrastructure limitations of the selected terminals in those ports.

3.3. Modules of CCM

Besides the input parameters, the CCM entails three main models: the maritime or ship model, the port model, and the hinterland model. These models are further explained in the following sections. Figure 3.8 provides a schematic view of these models with their relevant details.

Figure 3. 8: Modules of CCM



Source: Author composition based on van Hassel et al. 2016a

3.3.1. Maritime ship model

The maritime or ship model encompasses four main parts such as (i) routing module, (ii) design module, (iii) cost module, and (iv) generalized cost. The properties of each module are explained in the following paragraph/table.

3.3.1.1. Routing Module

In this module, complete loops between ports are pre-programmed. A maritime distances database is built, linking all the available ports. The distances are determined using AXSmarine (2014) (van Hassel et al. 2016a). In this module, the *operational features* of the ship are defined and classified into three fields such as (i) the speed of the ship, (ii) payload of the ship, and (iii) fleet calculations that are plotted in Table 3.1.

Table 3. 1: Operational features of the routing module

Operational properties of the vessel					
Speed of the ship		**The payload of the ship** *		**Fleet Calculations** **	
Property	Value	Property	Value	Property	Value
% speed of the design speed [knots]	90 % ****	Average payload ship (% of payload)	80%	Departure frequency of the vessel	[Days] *
Port approach speed	10 [knots]				
Speed in the port	5 [knots]				

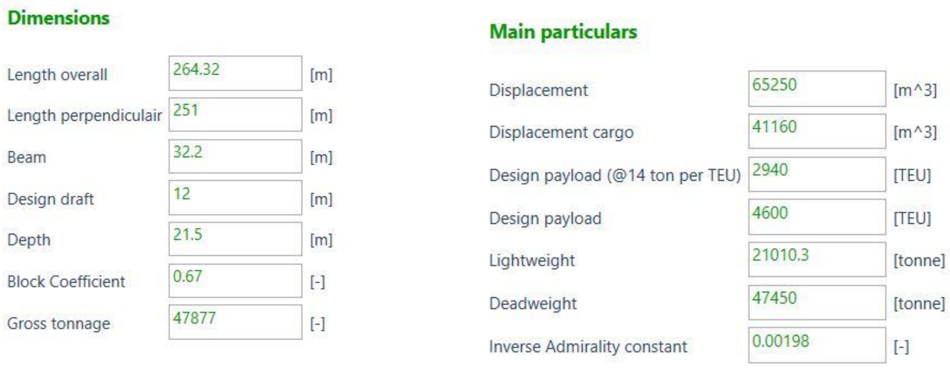
** It is possible to calculate payload-based loading in port or not.*
*** It is possible to estimate one vessel or fleet analysis.*
**** It is not a fixed value and can be assigned correspondingly.*
***** % speed of the design speed is 90% by default.*

3.3.1.2. Design or Technical Module

The design module, which is a parametric one, is utilized to determine the technical features of the vessel. The *technical properties* of the chosen ship contain five significant components.

I. *Dimensions (length overall, depth, etc.)*
II. *Main particulars (displacement cargo, design payload, deadweight, etc.)*
III. *Propulsion parameters: Installed power, design speed, the fuel consumption of the engines, type of fuel used either HFO, MDO, and LNG, and scrubber option. It is also possible to define the fuel used inside ECA and outside ECA zones.*
IV. *Cargo Handling: handling rate [TEU/Hour] and handling cost [EUR/TEU] can be specified. A vessel with a geared type can also be defined here.*
Emission of fuels: As three fuels, namely HFO, MDO, and LNG, are pre-defined in the model, it is possible to insert the input value of their emitted pollution for four different pollutants of SO_x, NO_x, CO_2, and PM_{10}.

Figure 3. 9: Technical properties of a ship



Indeed, these technical components can specify whether a particular ship can enter a specific port contingent on features and limitations such as quay lengths (van Hassel et al. 2016a).

3.3.1.3. Cost Module

In this module, the transport cost is computed, which is dependent on the results of routing and design modules. For this purpose, the cost components are defined and classified into three main groups as running cost, voyage cost, capital cost (Drewry, 2005). The equation of each cost component is obtained from (van Hassel et al. 2016a).

Running or Operational Cost:

This cost comprises five components, namely crew cost, insurance cost, consumables cost, repair and maintenance costs, management and administration cost (Drewry, 2005), indexed to 2012 values by applying index numbers (van Hassel et al. 2016a). The operational cost of a ship is calculated based on Equation 3.1:

$$OC_i = (CC_i + IN_i + CON_i + RM_i + MA_i i) * \frac{DIST_K}{Vi} \qquad \text{(Eq. 3.1)}$$

In which:

OC_i = Operational cost of the ship size i [EUR/loop]
CC_i = Crew cost of the ship size i [EUR/Hour]
IN_i = Insurance cost of the ship size i [EUR/Hour]
CON_i = Consumables costs of the ship size i [EUR/Hour]
RM_i = Repair and maintenance costs of the ship size i [EUR/Hour]
MA_i = Management and administration costs of the ship size i [EUR/Hour]
$DIST_k$ = Distance sailed in a given loop k [nm]
V_i = Speed of the ship size i [knots]

Voyage Cost:

The voyage cost has four main elements: fuel, lubricant, canal, and port dues, calculated based on Equation 3.2.

$$VC_i = (FC_i(V_i) + LUB_i) * \frac{DIST_k}{V_i} + CD_i + PD_{i,j} \qquad \text{(Eq. 3.2)}$$

In which:

VC_i = Voyage cost of the ship size i [EUR]
FC_i (V_i) = Fuel cost of the ship size i at speed V_i per sailed hour [EUR/h] (see van Hassel et al. (2016) for more details on this calculation.
LUB_i = Lubricants costs of the ship size i per sailed hour [EUR/h]
$DIST_k$ = Distance sailed for vessel i between two ports in a given loop k [nm]
V_i = Speed of the ship size i [knots]
CD_i = Canal dues for vessel type i [EUR]
$PD_{i,j}$ = Port dues of vessel type i at port j [EUR]

Capital Cost:

Three main components, such as interest cost, depreciation cost, and total time are required for the calculation of the capital cost of a ship in which total time depends on the sailing time at a speed of the ship of size i (V_i) and total port time in all the ports. The capital cost of a vessel is computed based on Equation 3.3.

$$CapC_i = (DEP_i + INTER_i) * \frac{T_k}{365} \qquad \text{(Eq. 3.3)}$$

In which:

$CapC_i$ = Capital cost of a ship size i [EUR]
DEP_i = Depreciation cost a ship size i [EUR/year]
$INTER_i$ = Interest cost of a ship size i [EUR/year]
T_k = Total time that a ship size i spends in the loop k [Day]

Besides, the ship's purchase price [EUR] needs to be specified, which is a variant based on the size of the vessel, which is imperative to calculate the depreciation and the interest. Mulligan (2008) develops a model to estimate the new building cost of a container ship based on the size (dwt) of the ship (van Hassel et al. 2016a).

3.3.2. Port Model

The different processes in the port are included in the model. It is considered by applying queuing theory in the port process. The linkages between other chain elements with varying capacities are taken into account through the queuing theory application. At the terminals, loading and unloading the ships is modeled. First, the ship has to sail from the terminal entrance to the quay wall. The vessel is moored, and containers will be handled.

The handling time is related to the number of cranes per ship length deployed and the nominal handling rate of the cranes. If more containers are handled (due to the increase in ship size) or when more container ships enter a terminal, the total handling time will increase. Finally, the model can evaluate the total time and cost per ship for each terminal in the port and thus the generalized cost in the port phase (van Hassel et al. 2016a & 2020).

In this section, the cost components in the port process when a ship enters the port are described. These costs are divided into three main elements: port shipping cost, port authority cost, and third-party cost and are paid by the ship owners. Table 3.2 plots each cost component.

Table 3. 2: Port model cost components

Port model cost	Definition
Port shipping cost	This cost depends on the size and type of the ship using the port, including maintenance and operation costs such as fuel consumption during the port stage and crew costs when the ship is in the harbor.
Port Authority cost	Port authority or port dues cost is the cost that the shipowner needs to pay to the port authority. Each port has a specific system of setting charges, and consequently, the estimation process is different from port to port.
Third-party cost	It is made out of three elements such as (i) cargo-handling cost, (ii) cost for the utilization of tug boat, which is dependent on the ship size and type, and (iii) cost for the application of pilotage.

Source: Author's composition based on van Hassel et al. 2016a.

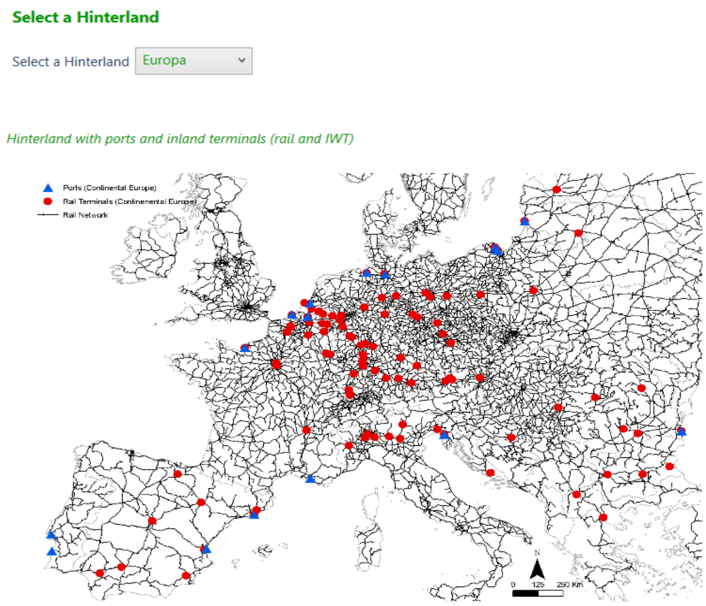
3.3.3. Hinterland model

A hinterland model is developed to calculate the hinterland transport cost from a selected terminal to the NUTS-2 European hinterland regions. The distance data [10] is required for the estimation of the cost of the hinterland transport in which the distances from the available terminals in the ports to all the hinterland regions are defined by including intermodal hinterland transportation, which means for two different perspectives (van Hassel et al. 2016a & 2016b & 2018): (i) distances for the road connections to the center of the hinterland regions (NUTS-2 regions) (ii) distance for rail connections

[10] The data is provided by Antwerp Port Authority (2014).

and the inland waterway to the inland terminals. For the latter case, the distances from inland terminals to the center of the hinterland regions are also determined.

Figure 3. 10: Hinterland regions in Europe in the model



Various sources have acquired the relevant distance data for road, rail, and inland waterway connections. Table 3.3 plots the reference source of each type of data.

Table 3. 3: Source and hinterland distance data types

Type of Data	Source
Inland waterway distances	Euro Global Map Data (2015)
IWT Distance from the port terminal to the inland waterway terminal	Utilizing the shortest path algorithm over the inland waterway network
Distance from inland terminal to the center of the region	Utilizing Google Maps algorithm
Rail distance data	Eurostat (2015)
Rail Distance from the port terminal to the rail terminal	Utilizing the shortest path algorithm over the rail network
Road Distance from the rail terminal to the center of the region	Utilizing Google Maps algorithm

Source: Author's composition based on van Hassel et al. 2016b

In the hinterland model, the generalized costs of three modes of transportation, namely rail, road, and inland waterways (where applicable), are computed based on Equation 3.4.

$$GC_j = OPC_j + C_{handling} + U_j * VoT \qquad \text{(Eq. 3.4)}$$

In which:

GC_j = Generalized cost of the transport mode j [EUR/TEU]
OPC_j = Out of pocket cost of the transport mode j [EUR/TEU]
$C_{handling}$ = Handling cost [EUR/TEU]
U_j = Total hinterland travel time of the transport mode j [h]
*VoT = Value of time [EUR/TEU*h]*

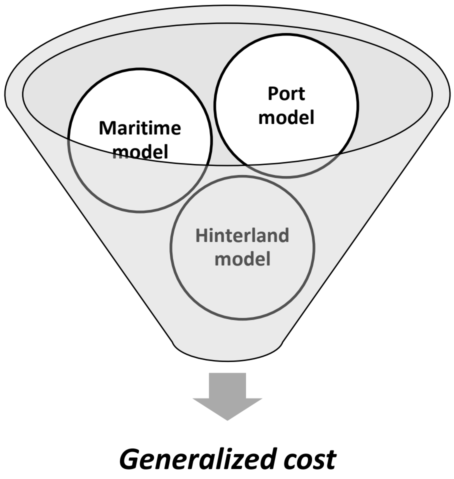
The time cost is considered the total travel time of the transport mode j, including loading time, unloading time, waiting time due to the congestion. Furthermore, the value of time is considered the opportunity cost during transportation [11]. Additionally, distance cost (such as fuel cost) is determined based on the actual moving through a hinterland transport mode and is added to the time cost (van Hassel et al. 2016a).

[11] To estimate the cargo values, O'Sullivan (2010) provides an overview of the values of cargo transported as a function of the ports where cargo loading happens.

3.4. Generalized Cost

The models mentioned above are imperative to estimate the generalized chain cost in each loop. The generalized cost is calculated in all the three maritime, port, and hinterland models in which these are summed to acquire the overall chain cost.

Figure 3. 11: Generalized chain cost



To calculate the generalized chain cost (EUR/TEU) from the point of origin (i) in the hinterland (A) to a destination point (j) in another hinterland (B), the model takes into account various cost items. The generalized cost is composed of two main elements (i) monetary (out of pocket) cost and (ii) non-monetary cost. The monetary cost of maritime transport includes operational, voyage, and capital cost of the ship size i, which is considered the ship's total cost. Next, the out-of-pocket cost [12] includes other costs belonging to the different chain cost elements. In contrast, the non-monetary part is the monetized value of the time spent in the maritime journey and is related to the flexibility, service, reliability, port information system quality.

Equation 3.5 explains the generalized chain cost calculation.

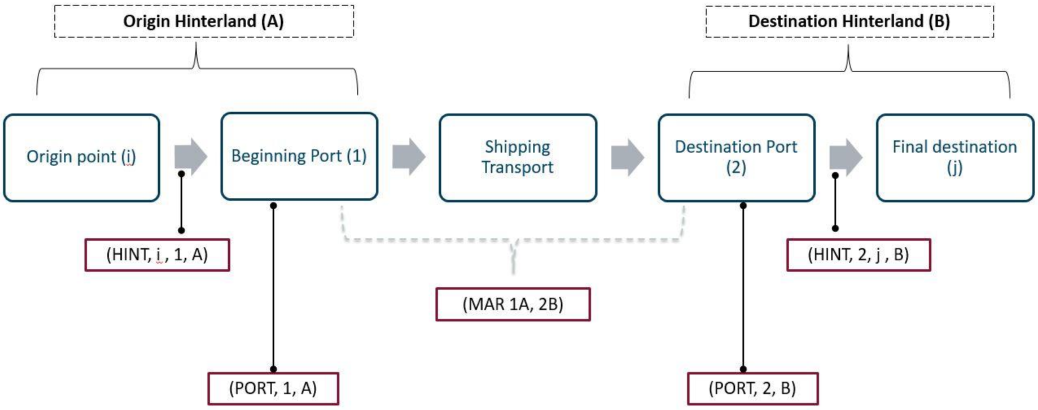
$$GC_{i,j}i = OPC_{i,j} + T_{i,j} * VoT_k \qquad \text{(Eq. 3.5)}$$

$GC_{i,j}i$ = Generalized cost of container transport by ship size (i) traveling from port of origin (i) to the port of destination (j) [EUR/TEU]
$OPC_{i,j}$= Out of pocket cost [EUR/TEU]
$T_{i,j}$ = Total transport time from the point of origin (i) to the destination point (j) [h]
*VoT_k = Value of time of product type k [EUR/TEU*h]*

As explained, the chain comprises three main segments, namely maritime, port, and hinterland transportations. The costs of these parts should be considered in the model. Figure 3.12 draws the MarSC and highlights the relevant cost components in each segment.

[12] OPC $_{i,j}$ is the cost for performing the transport (in this case, hinterland, port, maritime, port and hinterland).

Figure 3. 12: Segments of the MarSC



Source: Author's composition

- ⇨ Hinterland transportation cost: This cost should be considered in both chain legs. Thus, it has two components:
  - (HINT, i, 1, A): Cost of transporting the cargo from the origin point (i) to the beginning port (1) in the origin hinterland region (A)
  - (HINT, 2, j, B): Cost of transporting the cargo from destination port (2) to the final destination (j) in the destination hinterland region (B)
- ⇨ Port process cost: This cost includes two elements:
  - (PORT, 1, A): Port-related cost of the container in the beginning port (1) in the origin hinterland region (A)
  - (PORT, 2, B): Port-related cost of the container in the destination port (2) in the destination hinterland region (B)
- ⇨ Maritime shipping cost:
  - (MAR 1A, 2B): The maritime cost of transporting the cargo via sea from the beginning port (1) in the origin hinterland region (A) to the destination port (2) in the destination hinterland region (B). The out-of-pocket cost encompasses the maritime leg's operational, voyage, and capital costs.

By knowing all the three segments of the chain, Equation 3.5 can be re-written as:

$$GCi,j = GC_{HINT,\, i,\, 1,\, A} + GC_{PORT,\, 1,\, A} + GC_{MAR,\, 1A,\, 2B} + GC_{PORT,\, 2,\, B} + GC_{HINT,\, 2,\, j,\, B}$$
(Eq.3.6)

$$T_{i,j} = T_{HINT,\, i,\, 1,\, A} + T_{PORT,\, 1,\, A} + T_{MAR,\, 1A,\, 2B} + T_{PORT,\, 2,\, B} + T_{HINT,\, 2,\, j,\, B} \qquad \text{(Eq. 3.7)}$$

Therefore, the out-of-pocket cost is calculated in detail based on Equation 3.8:

$$OPC_{i,j} = OPC_{HINT,\, i,\, 1,\, A} + OPC_{PORT,\, 1,\, A} + OPC_{MAR,1A,\, 2B} + OPC_{PORT,\, 2,\, B} + OPC_{HINT,2,\, j,\, B} \qquad \text{(Eq. 3.8)}$$

As indicated in Equation 3.5, the non-monetary part is monetized by multiplying the value of time and the total transport time. The total transport time includes all the time consumed in the chain segments from the origin to the destination. Therefore, the model takes into account the following periods: (i) the total transport time from a hinterland region (including a dwell time at an inland terminal for rail or IWT) to a port, (ii) the dwell time of a container at a deep-sea port, (iii) the maritime transport time and (iv) the inland transport time at the destination hinterland.

Chapter 4: Economic impact analysis of installing an SRA under the BWM Convention

4.1. Introduction

BW is necessary for the safe and efficient operation of shipping by satisfying the stability requirements of a ship. However, the disposal of BW causes harmful effects on the marine environment, which lead to economic loss and negative impact on the ecosystem and human health (David et al. 2007; Scriven et al. 2015; Lloyd's Register, 2016; Castro et al. 2017; Jee and Lee 2017; Kuroshi et al. 2019). BW discharge is a known high-risk vector globally (Chan et al. 2013), and it is considered the main vector of the introduction of Harmful Aquatic Organisms and Pathogens, which includes Non-Indigenous Species (Scriven et al. 2015; Rey 2018). In shipping, organisms are transferred with BW, in-tank sediments, and attached to the ships' hull or sea chests (David et al. 2007).

IMO recognizing the importance of BW as a vector, has been striving for many years to manage BW discharges through its Marine Environmental Protection Committee (MEPC) (Barry et al. 2008). Consequently, to prevent and solve these problems, the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention) was adopted in February 2004 by the IMO (IMO 2004; Jee and Lee 2017; Rey 2018). The BWM Convention was ratified and entered into force on September 8th, 2017. In the BWM Convention, ships must have onboard and implement an approved BWM Plan. Besides, a set of 15 guidelines regarding BW exchange, sampling, treatment systems, risk assessments, and management plan provides technical guidance to support the implementation of the convention's principles (Cheng et al. 2019).

Exemptions are applied when a risk assessment (RA) based on the IMO G7 Guidelines is acceptably low risk. Several researchers and governments have analyzed and determined the viability of a so-called SRA to apply for this exemption. An SRA is an exemption area within the BWM convention; in this SRA, it is not necessary to treat the BW, and it can be loaded and unloaded anywhere within the SRA. There are various definitions of SRA in the literature. According to David et al. 2013, permanent exceptions from BWM requirements may apply when the uptake and discharge of BW occur at the *same location*.

Moreover, the shipping industry benefits from a larger location, as it avoids BWM requirements on voyages inside each location while maximizing the protection of the environment requires that the same location be as small as possible. Thus, it is not only about the size of the area but, more importantly, on the same ecological status. As a result, the same location may be of different dimensions, including a mooring, port basin, port, anchorage, part of a sea, or even an entire sea with numerous ports. However, Olenin et al. 2016 mention that it would be more problematic if exemptions from BWM requirements spanning large geographical areas (e.g., across national boundaries, more than one regional sea).

Saunders and Drillet 2016 defined the SRA as "An area delimited by the high probability of natural spread of target species that potentially present a risk of bio-invasion via ballast water." Furthermore, SRA refers to an area-based approach for the risk assessment of aquatic invasive species that considers the extent of natural dispersal (Stuer-Lauridsen, Drillet, Hansen, & Saunders, 2018). The IMO concluded that an SRA should be defined as “an agreed geographical area based on completion of a risk assessment carried out in line with these Guidelines (IMO 2017; Stuer-Lauridsen et al. 2018).

This research aims to determine the economic consequences for a possible SRA in (part of) the Netherlands and Belgium waters in which it takes an economic perspective and analyses the economic effects of a BWM in SRA. Two neighboring countries are selected because these countries host the most important European ports, having a lot of deep-sea and short-sea traffic and access to information and data. Moreover, this chapter develops a new typology and cost-benefit estimation for SRA establishment, which can be applied worldwide for all types of vessels based on BW assumption.

Although there is a confrontation between the ecological and economic incentives of establishing an SRA, the goal is not to evaluate the confrontation between economy and environment in this chapter. Still, the purpose is to develop a method that allows quantifying the economic viability of an SRA under the condition that all the ecological requirements are fulfilled in the North Sea between the Netherlands and Belgium. Therefore, this research study assumes that the ecological risk of the considered ports is assessed and complied with the IMO G7 guideline, and the results are accepted for the exemption of BW treatment and establishment of SRA. Hence, the biological point of view is approved.

The investigated research questions are :

- *Which ports and shipping routes can be selected and why?*
- *Which vessel types and ship sizes are affected?*
- *What are the costs and benefits of having an SRA? And in particular, what is the benefit for vessel owners of using an SRA?*

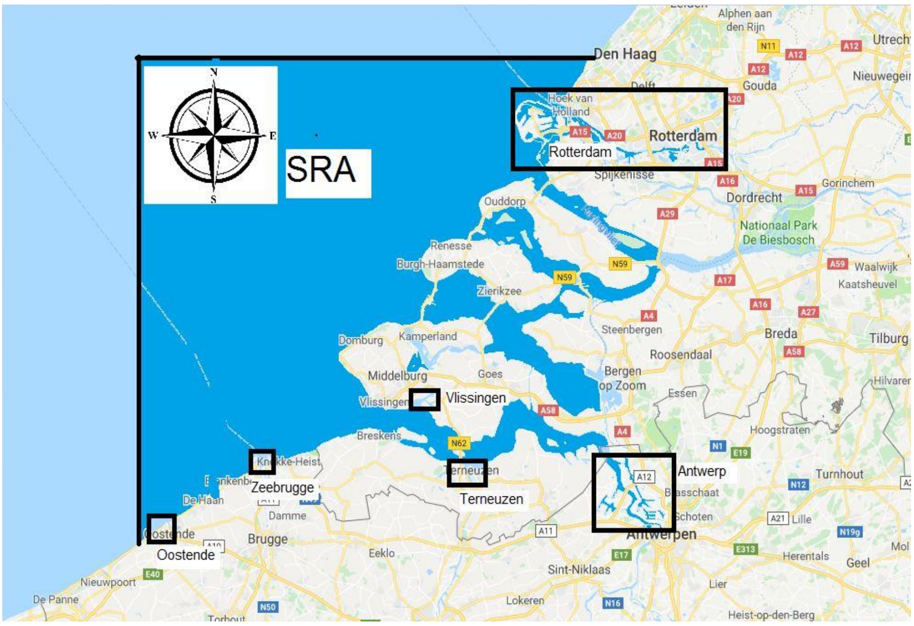
To determine the scope of the research, firstly, the main maritime locations and their characteristics within the possible SRA are identified. The SRA includes five Dutch and Belgian ports in this study, namely Rotterdam; Zeeland Seaports (Terneuzen and Vlissingen[13]); Antwerp; Zeebrugge, and Ostend of the essential ports within this geographic region (Figure 4.1).

The maritime network within this geographic region is diverse. On the one hand, the biggest seagoing vessels (both bulkers and containerships) come to ports within this geographic area; on the other hand, many smaller inland ships operate within the port towards the hinterland. Rotterdam and Zeeland Seaports are ‘importing’ ports, while Antwerpen and Zeebrugge are ‘exporting’ ports, which means the outgoing flows are more than or almost the same as the incoming flows. Based on the definition of SRA, BW does not need to be treated if the vessel movements occur between two ports

[13] In this study, only the Zeeland seaports (Terneuzen and Vlissingen) are considered, while the port of Ghent is not considered in this research due to the fact the salinity is high in this port which makes that most of the available organic species in the water will be killed anyway. Therefore, the data is at the level of the Zeeland seaports (Terneuzen and Vlissingen ports) and not at the level of North Sea Port.

from the same country. Thus, only the vessel movements are considered between either Rotterdam or Zeeland Seaport on the one hand, and Antwerp, Zeebrugge, and Ostend on the other hand, and vice versa.

Figure 4. 1: Possible SRA area and ports



Source: Authors composition

The methodology applied in this research is the evaluation of the quantification of the economic effects of setting up an SRA. A two-step approach is used; First, the likely profit of having an SRA is estimated. As the second step, the cost of establishing the SRA is computed, which leads to calculating the total net benefit.

The methodology considers the characteristics of the BWM Convention of an SRA and the maritime locations within the possible geographic area of an SRA.

This chapter includes all three aspects of sustainability: environmental, economic, and social dimensions. Furthermore, this research pertains to the UN SDG 12 "*to achieve the environmental management of chemicals and all wastes and significantly reduce their release to air, water, and soil to minimize their adverse impacts on human health and the environment*" and SDG 14 "*to manage and protect marine and coastal ecosystems to avoid significant adverse impacts*."

This chapter is based on the published paper by Mohseni et al. 2021. The rest of the chapter is organized in the following way. Section 4.2 reports the literature review regarding BWM regulations, exemptions, and treatment systems. Section 4.3 explains the methodology. Section 4.4 presents an overview of the collected data. Section 4.5 reports the obtained results on the benefits of establishing the SRA and discusses the sensitivity analyses. Section 4.6 provides the generalization of the applied methodology to other regions. Finally, the last section (section 4.7) outlines the primary outcomes and conclusions.

4.2. Literature review

The literature review is structured into four sub-sections. Sub-section 1 reviews BWM regulations. The BWM Convention and other legislations applied worldwide to manage BW are discussed here. Sub-section 2 and 3 explain the BWM exemption based on the BWM Convention. It deliberates the Risk Assessment (RA) methods for granting exemptions and provides various samples of BWM exemption around the world. Sub-section 4 describes the treatment systems and available technologies for BWM. Finally, sub-section 5 presents an extensive review of the recent research and applied case studies related to BWM.

4.2.1. BWM Regulations

The BWM Convention includes two performance standards for BW discharge, namely D-1 and D-2. The performance standard D-1 is based on BW exchange, while the standard D-2 addresses Ballast Water Treatment Systems (BWTS), and it specifies the levels of viable organisms that are allowed to remain in the water after treatment. Following the entry into force in 2017, vessels whose keels are laid on or after 18 September 2017 must comply with the D-2 standard (NEPIA, 2019). Apart from BWM regulation, other important legislation, for instance, the European Union and The United States Coast Guard, are implemented to manage the BW system [14].

Table 4. 1: IMO BW management regulation

Regulation	Applicability	Compliance schedule
The BWM Convention	The BWM Convention applies to all ships, including submersibles, floating craft, floating platforms, Floating Storage Units (FSUs), and Floating Production Storage and Offloading (FPSOs). It does not apply to ships not designed to carry BW/ships not operating in international waters/warships, naval auxiliary ships, or other ships owned or operated by a state/ships only on non-commercial service, or vessels with permanent BW in sealed tanks. All vessels of 400 gross tons and above will be required to have onboard an approved BWM Plan and a Ballast Water Record Book, while vessels below 400 gross tons will be subjected to national survey and certification regimes.	The BWM Convention will enter into force 12 months after ratification by 30 states, representing 35 percent of the world's merchant shipping tonnage. Once the BWM Convention has entered into force, all ships will be required to manage their BW on every voyage by exchanging or treating it using an approved BWTS.

Source: Own composition based on Lloyds Register 2016, IMO 2017, and NEPIA 2019

Based on BWM Convention, an exemption may be granted to a ship on a voyage or voyages between specified ports or locations or to a vessel that operates exclusively between specified ports or areas. Next to IMO, other regulators such as European Union and The United States Coast Guard apply different regulations to treat BW in their territories.

[14] See Appendix A for further information regarding approach of BW in several regions around the world.

Table 4. 2: Other BW management regulations

<table>
<tr><th>Regulation</th><th>Applicability</th><th colspan="3">Compliance schedule</th></tr>
<tr><td>European Union regulations</td><td>EU Regulation 1143/2014 on invasive alien species (Regulation (EU) No 1143/2014 of the European Parliament and the Council on the prevention and management of the introduction and spread of invasive alien species).</td><td colspan="3">It entered into force on 1 January 2015. The regulation “seeks to address the problem of invasive alien species comprehensively to protect native biodiversity and ecosystem services, as well as to minimize and mitigate the human health or economic impacts that these species can have.”</td></tr>
<tr><td rowspan="5">The United States Coast Guard (USCG) regulations</td><td rowspan="5">All ships calling at US ports and planning to discharge BW must carry out BW exchange or treatment in addition to sediment management.</td><td>Vessel</td><td>Ballast water capacity</td><td>Compliance date</td></tr>
<tr><td rowspan="2">New vessels</td><td>All – Built on or after 1 December 2013</td><td>On delivery</td></tr>
<tr><td>Less than 1,500m^3 Built before 1 December 2013</td><td>First scheduled dry-docking after 1 January 2016</td></tr>
<tr><td rowspan="2">Existing vessels</td><td>1,500 – 5,000m^3 Built before 1 December 2013</td><td>First scheduled dry-docking after 1 January 2014</td></tr>
<tr><td>Greater than 5,000m^3 Built before 1 December 2013</td><td>First scheduled dry-docking after 1 January 2016</td></tr>
</table>

Source: Own composition based on Lloyds Register 2016, IMO 2017, and NEPIA 2019

4.2.2. BWM and Risk Assessment

Risk assessment is a logical process for assigning the likelihood and consequences of specific events, such as the entry, establishment, or spread of harmful aquatic organisms and pathogens. Risk assessments can be qualitative or quantitative and can be a valuable decision aid if completed systematically and systematically (MEPC, 2017). Several principles need to be respected to perform the risk assessment, as reported in Table 4.3.

Table 4. 3: Key issues in risk assessment

Key principle	Definition
Effectiveness	Risk assessments accurately measure the risks to the extent necessary to achieve an appropriate level of protection.
Transparency	evidence supporting the action recommended by risk assessments, and areas of uncertainty are documented and made available to decision-makers.
Consistency	Risk assessments achieve a uniformly high level of performance

Comprehensiveness	full range of values, including economic, environmental, social and cultural, are considered when assessing risks and making recommendations.
Risk management	Low-risk scenarios may exist, but zero risk is not obtainable, and as such, risk should be managed by determining the acceptable level of risk in each instance.
Precautionary	Risk assessments incorporate a level of precaution when making assumptions and recommendations, accounting for uncertainty, unreliability, and inadequacy of information
Science-based	Risk assessments are based on the best available information that has been collected and analyzed using scientific methods
Continuous improvement	Any risk model should be periodically reviewed and it is updated to account for improved understanding.

Source: Own composition based on MEPC 2017

In undertaking risk assessment when considering granting an exemption, the risk assessment principles should be carefully applied.

4.2.2.1. Risk assessment methods

There are two fundamentally different risk assessment approaches under the BWM Convention: the selective and the blanket approach. A blanket approach means that all ships intending to discharge BW in a port are required by the port State to conduct BWM. In comparison, the selective process means that appropriate BWM measures are required depending on different risk levels posed by the intended BW discharge. There are two cases, such as (i) ships may be exempted from BWM requirements provided that the risk level of a BW discharge is acceptable based on the G7 Guidelines (ii) if the risk is identified as (very) high, ships may be required to take additional measures based on G13 Guidelines (David and Gollasch 2015).

Regulation A-4 states that an exemption may only be granted 'based on the guidelines on risk assessment in G7'. Under G7, *three risk assessment* methods are recommended concerning granting an exemption following regulation A-4.

Table 4. 4: Risk assessment methods

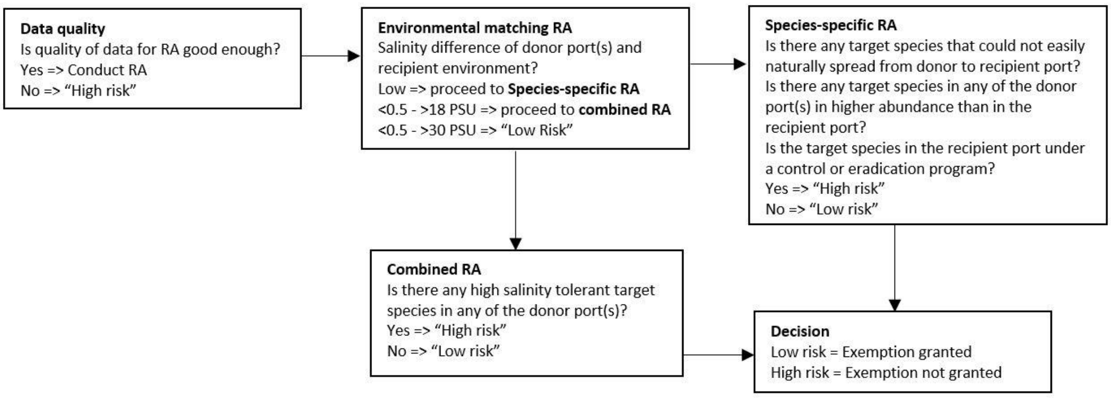
Risk assessment method	Definition	Necessary data
Environmental matching	It relies on comparing environmental conditions, including temperature and salinity, between donor and recipient regions.	(i) Origin of the ballast water to be discharged in recipient port, (ii) biogeographic region of donor and recipient port, and (iii) average and range of environmental conditions (salinity and temperature)

Species biogeographical	It is based on comparing the biogeographical distributions of nonindigenous, cryptogenic, and harmful native species that presently exist in the donor and recipient ports and biogeographic regions. It also evaluates environmental similarity and identifies high-risk invaders.	(i) records of invasion in the donor and recipient biogeographic regions and ports, (ii) records of native or non-indigenous species that could be transferred through ballast water in the donor biogeographic region, (iii) records of native species in the donor region that have the potential to affect human health or result in ecological or economic impacts
Species-specific	It evaluates the distribution and characteristics of individual target species, comparing their features with the environmental conditions within the ports in question to determine the likelihood of transfer and survival.	(i) evidence of prior introduction, (ii) demonstrated impacts on the environment, economy, human health, (iii) strength and type of ecological interactions

Source: own composition based on David and Gollasch (2015), Saunders and Drillet (2016), MEPC (2017)

Moreover, in 2015, David and Gollasch developed a framework for the risk assessment for the exemptions of BW treatment.

Figure 4. 2: Framework for the RA for exemptions



Source: own composition based on David and Gollasch (2015)

Based on this framework, salinity is the only reliable parameter for the environmental matching RA.

4.2.3. BWM Exemption

The BWM Convention also includes provisions for cases where vessels do not need to manage their BW (i.e., Regulation A-3 Exceptions and Regulation A-4 Exemptions) (IMO 2007). Exemptions are enabled when a risk assessment (RA), prepared according to the IMO G7 Guidelines, results in an acceptably low risk. It is specific for a ship, or different ships, sailing only between specified ports or locations. Exemptions are granted for up to five years but may be withdrawn if the risk becomes unacceptable during this period (IMO 2007; David and Gollasch 2010; David and Gollasch 2015; Olenin et al. 2016; Cheng et al. 2019). Regulation A-4 provides exemptions so long as the exemptions are, among other things, granted based on a risk assessment (Barry et al. 2008). The application of an exemption or a permanent exception means that a vessel is not required to install a BWTS, thus avoiding capital and operational costs as well as burdens associated with certification and inspections (David et al. 2013).

Vessel exemptions from BWM activities are often based on geographic designations, assuming that vessels traveling exclusively within these regions pose a reasonably low risk of transporting non-indigenous species (Verna & Harris, 2016). The convention recognizes that ships trading in specific locations and on voyages between certain ports may be considered a non-significant risk regarding the transport of invasive species via BW, and therefore, the use of a BWTS may not be necessary (Stuer-Lauridsen et al. 2018). A general exemption means that ships exclusively operating within the designated area will be allowed to operate without the need to install BW treatment technologies. Vessels that operate regularly or occasionally to and from an SRA will still need to treat the BW as required by the BWM Convention (Hansen & Christensen, 2018). Based on the relevant literature, it is observed that most exemptions are developed nationally and regarded as interim, which includes exemptions for ships operating on fixed routes or short sea voyages (Olenin et al. 2016). Table 4.5 plots some of these exemptions around the world.

Table 4. 5: Exemption of BW in different countries

Region	Exemptions
Canada	Vessels operating exclusively in Canadian waters/ships that run solely in the Great Lakes / small research vessels/vessels with permanent ballast and government vessels.
New Zealand	The standard does not apply to BW that will not be discharged in New Zealand waters/BW loaded in New Zealand waters/or emergency discharge of BW. New Zealand accepts discharges of BW, which was either (i) exchanged at sea in areas free from coastal influences, preferably 200 NM from the nearest land, and in water over 200 m in depth (ii) is freshwater (not more than 2.5 ppt sodium chloride) (iii) treated with a shipboard treatment system; or (iv) discharged in an onshore treatment facility.
United States	Vessels are operating within a single Coast Guard zone/vessels which travel no more than 10 nm without crossing physical barriers (e.g., locks) / vessels operating exclusively on the Great Lakes; and / inland and seagoing ships less than 1600 gross registered tons.

Source: Author's composition based on MAF 2005; Albert et al. 2013; ABS 2014; David and Gollasch 2015; Olenin et al. 2016

Vessels are exempted from BWM requirements when conducting intra-coastal voyages along with the U.S. West Coast parts. However, each U.S. Pacific coastal state has unique BWM requirements (David et al. 2013). The United States provides a BWM exemption for vessels traveling within one USCG COTP Zone and vessels on short-distance voyages (Verna & Harris, 2016). Furthermore, Canada provides an exemption for ships that operate exclusively north of Cape Blanco, Oregon, or Cape Cod, Massachusetts (Transport Canada 2011; Scriven et al. 2015). A vessel that discharges unmanaged BW to British Columbia sourced north of Cape Blanco may influence the risk of species spreading to Alaska given proximity and opportunities for anthropogenic or natural dispersal (Verna & Harris, 2016).

4.2.4. Ballast Water Treatment Systems

Generally, the treatment process can be split into three stages: pre-treatment (to exclude as much as possible, solid material and bigger organisms), treatment, and residual control or neutralization, which is needed if there are any substances left in the BW after the treatment process (David and Gollasch 2015). Table 4.6 plots the treatment process and the leading technologies for the BW management system.

Table 4. 6: BW treatment process and different technologies

Pre-treatment	Treatment			Residual control
	Chemical	Physical	Biological	
Filtration	Chlorination	UV radiation	Bioaugmentation with microorganisms	Chemical reduction (Neutralization)
Hydro cyclone	Electro chlorination	Deoxygenation		
Coagulation	Ozonation	Inert gas or nitrogen injection		
Flocculation	Chlorine dioxide	Ultrasonic treatment		
	Peracetic acid	Cavitation		
	Other active substances	Fine filtration		
		Heat		

Source: own composition based on David and Gollasch 2015

BWTS is classified into two main groups; namely (i) *Non-active substances systems* which include UV, Filtration, Deoxygenation, Heat and deoxygenation, and (ii) *Active substances systems* which encompass Electrolytic, Advanced oxidation, and Ozone (IMO 2018; US Coast Guard 2018; Gerhard et al. 2019). Furthermore, treatment systems for BWM are divided into port-based and shipboard treatments (Tsolaki & Diamadopoulos, 2010). By definition, shipboard treatment includes BW exchange and onboard treatment, further divided into physical separation and secondary treatment using mechanical and chemical means (Jee & Lee, 2017).

On-board BWTSs differ in characteristics such as costs, capacity, and methodology. These systems are divided into three main categories and several sub-categories (Marine Insight 2017), namely (i) UV systems which include (a) ultra-violet treatment and (b) filtration systems (physical))[15]; (ii) Electrolytic systems, which consist of (a) acoustic (cavitation treatment) (b) electric pulse/pulse plasma systems (c) magnetic field treatment and (d) Heat (thermal treatment)); (iii) Chemical Injection systems, which encompass (a) chemical disinfection (oxidizing and non-oxidizing biocides) and (b) deoxygenation treatment.

The main decisive factor if a vessel will have either an onboard or shore-based BW system is dependent on the yearly volume of ballast (King, Riggio, & Hagan, 2010). King et al. (2010) found that a shore-based system is appropriate if a vessel processes less than 70,000 metric tons of BW per year. However, for ships handling more BW per year, an on-board system is better to use.

[15] Not only UV system, but could be categorized within multiple categories.

Recent research by Gerhard et al. (2019) studied the total number and dominant treatment systems in the United States and Australia. Based on this research, from 2007 to 2017, a total of 65 treatment systems received Type Approval and were reported to the IMO. Furthermore, this research reveals that the selection of the BWTS remains a difficult decision for ship owners because there is not yet long-term quality feedback on the functioning of systems. The factors influencing these decisions can vary in weight depending on ship-owner, vessel size, operating region, and cargo requirements. Besides, operation and maintenance costs are among the most critical factors involved in decision-making.

4.2.5. BWM - Research and Case Studies

Many researchers have worked, and many case studies have been performed globally in recent years related to BWM. Table 4.7 presents the objectives, approaches, and main results of each study.

Table 4. 7: Several studies on the BWM

Author(s)	Objectives and purposes	Methodology and approach
Barry et al. (2008)	To explore four principles that underpin risk assessment for natural resource management before evaluating two significant approaches to Ballast Water Risk Assessment (BWRA).	Two methods of assessing the risk of species by BW are discussed: (i) species-specific and (ii) environmental similarity assessments
David et al. (2012)	To assess the quantity of BW discharged as an essential element of the decision-making process in BW risk assessment and management.	A new generic Ballast Water Discharge Assessment (BWDA) model based on vessel cargo operation and vessel dimensions. Port of Koper, Slovenia.
Chan et al. (2013)	To characterize BW discharge patterns for different vessel pathways / To identify ports at relatively high risk of ballast-mediated invasions and the responsible vessel pathway.	Using BW transport in the Canadian Arctic as a case study.
Cope et al. (2015)	Based on historic ballast survey data, BW transfer models into Australian waters are constructed. BW discharge is modeled based on combinations of vessel type, vessel size, and destination port purpose.	A case study analysis: (i) quantifying vessel traffic, (ii) hindcasting BW discharge, and (iii) ranking the associated risk of biological invasion into Australian waters.
OSPAR and HELCOM (Helsinki Commission) (2015)	To provide a harmonized procedure following Art. 13 of the Convention for the issue of exemptions according to Regulation A-4 of the Convention	The Harmonized Procedure is split into seven sections: Introduction; Port Survey Protocol; Target Species; Data Storage; Risk Assessment; Decision Support Tool and; Administrative Procedures.
Castro et al. (2017)	To summarize the implementation of NORMAM-20 (unilateral regulation) of 10 years of enforcement (2005–	(i) Design and area of study: 11,183 vessels in 39 ports/terminals between 2005 and 2015 (ii) Data collection: Data

	2015) in 39 ports along the Brazilian coast.	collected from Port State Control reports on BW
David et al. (2018)	To assess and compare BW discharge profiles of two ports with other maritime traffic and cargo profiles, the Port of Hamburg (Germany) and the Muuga Harbor, Port of Tallinn (Estonia), for 2012.	Information about BW discharge volumes and donor ports may be obtained with Ballast Water Reporting (BWR) or a Ballast Water Discharge Assessment (BWDA). [16]
Hansen and Christensen (2018)	To apply the SRA concept to a specific area, including the Kattegat and Øresund region between Denmark and Sweden.	To perform an initial review using MIS databases and data portals to create a target list of species / To apply Same-Risk-Area Assessment Model (SRAAM) based on a Lagrangian approach.
Cheng et al. (2019)	To identify the risk factors to measure the risk level of ships and target high-risk vessels.	A combined method of the Delphi survey and analytic AHP approach.
David and Gollasch (2019)	Four routes covering intra-Adriatic voyages and voyages from ports outside the Adriatic Sea are selected to explain BWM RA using practical shipping examples.	BWM RA model results in four different risk levels. The BWM RA model was tested using shipping routes with ports inside and outside the Adriatic.
Kuroshi et al. (2019)	To develop a methodology to manage the likely operator error that could result from BWM System operations which can quantitatively assess and prioritize the contributions of Human Factors (HFs).	A combination of the Human Factor Analysis Classification System (HFACS), Analytic Hierarchy Process (AHP), and a modified version of the Theory of Inventive Problem Solving (TRIZ)

Source: Own composition based on reported references

Based on Table 4.7, a large variety of research has been performed under the subject of BWM and on different case studies. Several models and frameworks are developed to assess species' invasion risk by BW in the sea. It is observed that the source of BW and vessel characteristics are among the essential decisive elements for the selection of the risk factor and assess the level of risk related to BW. Moreover, the vessel's operational and BW discharge behavior has shown the best correlation between the vessel's cargo operation and the DWT. BW discharge has been considered one of the most important topics and has been assessed by several authors. It is found that the identification of donor ports is crucial to determine the level of risk posed by the BW to be discharged. Besides, BW discharge is modeled based on combinations of vessel type, vessel size, and destination port purpose.

The majority of existing literature considers the ecological assessment of the BWM Convention; however, to the best of the author's knowledge, almost none or a few studies investigate the evaluation of BWM in particular SRA from an economic standpoint. As the introduction of harmful aquatic organisms and pathogens to new environments was identified as one of the four most significant threats to the world's oceans (IMO 2021), it is necessary to address this issue not only from an ecological viewpoint and, but more importantly, from an economic evaluation. Therefore, the cost-benefit analysis of prospective BWM exceptions is examined in chapter four as the concept of establishing an SRA from an economic standpoint.

[16] BWDA does not identify the source of BW. In the lack of BWR, for vessels that have been assessed by the BWDA to have discharged BW, here, the last port of call was taken as the BW donor port. This approach is based on experience on BWDA studies conducted for the Port of Koper (Slovenia) where BWR is introduced.

In the next section, the applied methodology to calculate the cost and benefit of the SRA is explained. Besides, the typology of vessels that could benefit from the SRA, together with the estimation of their BW consumption, is defined.

4.3. Methodology

The applied method to assess the introduction of the SRA includes two main parts. First, the potential benefits of the SRA are quantified. In the second step, the cost of the SRA is appraised. Consequently, the total net benefits are computed based on the costs and benefits. This methodology is elaborated on more extensively in the following sections.

4.3.1. Benefits of the SRA

The main benefit of having an SRA is the saved operational cost for the vessel owners not to treat the BW. First, a definition of the vessels operating in the SRA is needed to calculate this benefit. Secondly, the two main options to treat the BW need to be considered. Based on this, a typology of vessels in the SRA and the primary calculation method of the benefits can be determined.

Definition of the vessel operations

If a vessel has a complete trip in an SRA, then the BW for that trip is not required to be treated [17]. However, most ships that sail into the defined SRA will also sail outside this SRA. It means that a potential benefit could be obtained only for the trip in the SRA. Vessels sailing from outside the SRA into a port of the SRA still need to have their BW treated. It means that, from the perspective of an SRA port, three different types of vessel operations are possible:

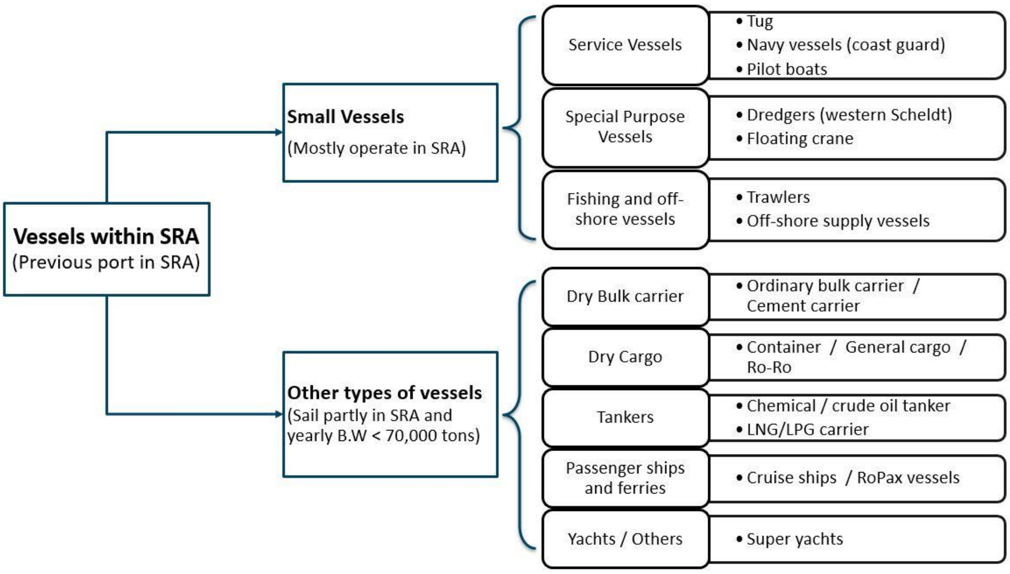
- *Vessels sail from outside the SRA to a port in the SRA.*
- *Vessels sail from an SRA port to another SRA port, but the previous port of call was outside the SRA. An example here could be a container vessel calling firstly in Hamburg, secondly in Rotterdam, and finally in Antwerp.*
- *Vessels sail from an SRA port to another SRA port, but the vessel is always operational. These are primarily small vessels such as service vessels, fishing, and offshore vessels (which sail from an SRA port to a location at sea and return to the same port).*

Typology of vessels in an SRA and their ballast water consumption

There is an extensive range of different vessel types sailing in the studied SRA. Based on the insights obtained in the previous sections, the main typology of vessels calling at an SRA port that could benefit from the SRA is defined and illustrated in Figure 4.3.

[17] If a trip is between two ports in the same country, then also no BW needs to be treated, due to the definition of the BW convention (the US is an exemption on this rule).

Figure 4. 3: Typology of vessels that could benefit from the SRA



Source: Author's composition

The vessels that are sailing only in the SRA are small. These vessel types include tug boats, pilot vessels, etc. These vessels typically have a minimal BW capacity. Tug boats and pilot boats, which are the vast majority of the ships permanently sailing in the SRA, do not have any water ballast. For fishing vessels/trawlers, also only a limited amount of BW is present. Therefore, the benefit of not treating the BW for these vessels is very low. This benefit is hence estimated at zero.

An additional calculation needs to be made for vessels with fewer than 70,000 tons yearly BW consumption.[18] The choice has been made to estimate an average BW consumption based on the statistics of the world fleet and the total worldwide seaborne trade. The total BW consumption can be calculated based on the worldwide trade volume.
David and Gollasch (2015) estimated that roughly 33% of the total worldwide trade volume in tons is used as BW by taking different ballast factors into account. From UNCTAD (2017), it is found that in 2016, 10,287 billion tons of cargo were transported. This means that 3,394,710,000 tons of BW were consumed in 2016. To determine the BW consumption per vessel group, the shares of each vessel group are multiplied by the total BW consumption. Table 4.8 plots the fleet data along with the calculated BW consumption.

Table 4. 8: Statistics of the world fleet and ballast consumption per vessel group

Vessel type	Total capacity [dwt]	Share [%]	BW consumption [ton/year]
Tankers	534,855,000	28.7%	974,281,770
Bulkers	796,581,000	42.8%	1,452,935,880
General cargo	74,823,000	4.0%	135,788,400
Container vessels	245,609,000	13.2%	448,101,720
Other			
Gas carriers	59,819,000	3.2%	108,630,720
Chemical tankers	43,225,000	2.3%	78,078,330

[18] Because no data is available at port level about the BW consumption per vessel type, some calculations are needed to estimate the average BW consumption.

Offshore	77,490,000	4.2%	142,577,820
Ferries	5,896,000	0.3%	10,184,130
Other	23,554,000	1.3%	44,131,230
	1,861,852,000	100%	**3,394,710,000**

Source: Own calculations based on Data from UNCTAD (2017)

It is observed from Table 4.8 that in 2017, 85% of the total world merchant fleet consisted of oil tankers, bulkers, and container vessels. These three-vessel groups are also responsible for 85% of BW consumption. More detailed vessel data is needed to calculate the average ballast consumption per vessel type. From van Hassel (2017), detailed fleet data is available for tankers, bulkers, and container vessels. Different vessel types are available for each vessel group and the number of ships (columns 1 to 3 in Table 4.9).

From the weighted share of each vessel type (column 4), it is possible to calculate the BW consumption for each sub-groups of vessels[19]. If the total BW consumption per vessel type is known, it is possible to calculate the average yearly BW consumption per year. Table 4.9 shows the results of the calculations.

Table 4. 9: Yearly BW consumption per vessel type

TANKERS	DWT (1)	Average capacity (DWT) (2)	Number of vessels (3)	Weighted share (4)	BW per vessel (ton/year) (5)
Product tanker	10,000-60,000	30,000	1,315	8.7%	64,680
Panamax	60,000-80,000	70,000	546	8.5%	150,921
Aframax	80,000-120,000	100,000	1,113	24.6%	215,602
Suezmax	120,000-200,000	160,000	528	18.7%	344,962
VLCC	200,000-320,000	260,000	606	34.9%	560,564
ULCC	320,000-550,000	435,000	48	4.6%	937,867
BULKERS					
Handysize	10,000-35,000	22,500	2,070	9.1%	63,543
Handymax	35,000-60,000	41,500	3,243	26.2%	117,202
Panamax	60,000-80,000	70,000	1,773	24.1%	197,690
Cape size	80,000	80,000	2,615	40.7%	225,932
CONTAINERS					
Small Feeder	1,000 TEU	1,000	948	4.6%	21,921
Feeder	1,000- 2,000 TEU	1,500	1,283	9.4%	32,881
Feeder max	2,000-3,000 TEU	2,500	673	8.2%	54,802
Panamax	3,000-5,000 TEU	4,000	920	18.0%	87,684

[19] The total BW consumption for containers, bulkers and tankers are known from Table 4.8. If it is applied the weighted share of each vessel sub group, then the total BW consumption for each of these sub groups can be calculated.

Post Pananmax	5,000-10,000 TEU	7,500	1,071	39.3%	164,407
New Panamax	10,000-14,500 TEU	12,250	265	15.9%	268,531
Ultra large	14,500 TEU	14,500	64	4.5%	317,853

Source: Own calculations based on vessel data from van Hassel (2017)

It can be seen that five vessel types have, on average, a yearly BW consumption of fewer than 70,000 tons per year. These vessel types are; (i) Product tankers (DWT< 60,000 tons); (ii) Handysize bulkers (DWT < 35,000 tons); (iii) Small feeder, feeder and feeder max container vessels (all container vessels smaller than 3,000 TEU capacity). Based on Statista (2018) data, the total number of general cargo vessels, gas carriers, and chemical tankers for 2017 is obtained. Therefore, these vessels' yearly average BW consumption can be computed by dividing the total BW consumption (obtained from Table 4.8) by the number of ships.

Table 4. 10: Total number and average BW consumption of general cargo, gas carrier, and chemical tankers

Type of vessel	Total number of vessel	Total BW consumption [ton/year]	Average BW consumption [ton/year]
General cargo	16,957	135,788,400	8,000
Gas carriers	1,850	108,630,720	58,720
Chemical tankers	5,418	78,078,330	14,410

Source: Own calculations based on Statista 2018

As a result of Tables 4.9 and 4.10, all the vessel types that consume less than 70,000 tons of BW per year are given in Table 4.11. It can be concluded that according to King et al. (2010), these vessels can be considered vessels that can use shore-based BWTS. To quantify the benefits of using the shore-based BWTS, the average BW consumption for a trip between two SRA ports needs to be known. This BW consumption is estimated based on the following formula:

$$BW_{j,X} = \frac{YBWC\ [\frac{tons}{year}]}{Operational\ days\ [\frac{trip}{year}]} \qquad \text{(Eq. 4.1)}$$

The BW consumption per trip between two SRA ports ($BW_{j,X}$) [Tons/trip] is calculated by dividing the yearly BW consumption (YBWC) by an average number of operational days per year for the different vessel types[20]. The average time needed for such a trip is more or less one day (column 3). The results are plotted in Table 4.11.

Table 4. 11: Overview of vessel types that could make use of shore-based BW systems

Vessel type	Size of the vessel (I)	Yearly BW consumption [tons/year] (II)	BW consumption in port X (tons/SRA trip) (III)
Product tanker	<60,000 dwt	64,680	258.72
Handy size	<35,000 dwt	63,543	254.17
Small feeder	<1,000 TEU	21,921	87.68

[20] The authors lack more detailed data for the actual operational days of the different vessels. Therefore, an estimation of 250 days per year is used for all vessel types.

Feeder	<2,000 TEU	32,881	131.53
Feeder max	<3,000 TEU	54,802	219.21
General cargo	All types	8,000	32.03
Gas carriers	All types	58,720	234.88
Chemical tankers	All types	14,410	57.64

Quantification of the benefits

Based on the developed typology, it is possible to calculate the benefits for each vessel calling at an SRA port. These benefits come from the saved cost for the vessel owners not having to treat their BW. Because vessels that operate mainly in the SRA are relatively small, most of these vessels will have a yearly BW consumption of fewer than 70,000 tons. Therefore, for the small vessels, the main benefit will come from the saved operational cost of not having to use a shore-based system. These yearly benefits can be quantified as follows:

$$Benefit_{Small,X} = \sum_{j=i}^{3}(\sum_{i=i}^{n}(BW_{j,X}.OC_j)_i) \qquad \text{(Eq. 4.2)}$$

With

Benefit $_{small,\ X}$ = yearly benefit of not needing to treat their BW for small vessels, calling at port x, sailing continuously in the SRA [EUR/year]

j = number of small vessels (from tugs to offshore supply vessels) that sail between two SRA ports

n = number of ships of each small vessel type sailing in the SRA

BW $_{j,\ x}$ = BW consumption for vessel type j in port x [ton/year]

OC$_J$ = operational cost for BW handling for vessel type j. These costs are estimated at 7.5 [EUR/ton] [21].

The benefits of the other types of vessels can be quantified as follows:

$$Benefit_{Other,X} = \sum_{k=1}^{5}(\sum_{j=1}^{m}(BW_{j,X}.OC_k)_l) \qquad \text{(Eq. 4.3)}$$

With

Benefit $_{Other,\ X}$ = yearly benefit for vessels sailing only partly in the SRA [EUR/year]

k = number of main other vessel types (bulk carriers, dry cargo vessels, etc.)

m = number of ships of each vessel type with a yearly BW consumption of fewer than 70,000 tons (i.e., tankers < 60,000 DWT, bulkers < 35,000 DWT, container vessels < 3,000 TEU, all general cargo vessels, gas carriers, and chemical tankers).

[21] Based on interview with Damen (2018), this value is assumed constant in all the SRA ports in this chapter.

4.3.2. Cost of the SRA

Besides the benefit of the SRA, some costs are related to installing and possibly also maintaining the SRA. The cost of establishing the SRA is determined by applying for an SRA exemption at the IMO while maintaining the SRA includes the cost of checks by persons who control the vessels on whether they comply with SRA rules. These checks involve validating if a specific ship has a previous port of call inside the SRA. For the cost of the SRA, there is an initial introduction cost of €2,000,000 at year 0 for the total SRA. The yearly maintenance cost of the total SRA is €200,000 per year ($C_{SRA,\ yearly}$), which involves on average 1 FTE per year per country (€75,000 per year multiplied by two countries) and port survey (€50,000 per year). This estimation includes all the costs for the preparatory meetings, papers, regulations, invasive species monitoring according to OSPAR HELCOM protocol (OSPAR and HELCOM, 2015), reporting, and emergencies, including the required personnel. The setup cost of the SRA is the cost of arranging the SRA at the IMO and the local governments.

4.3.3. The total net benefit of the SRA

The total net benefit per year of the SRA can be determined with the following equations:

$$Benefit_{year} = \sum_{x=1}^{5} B_{SRA,X} - C_{SRA,yearly} \qquad \text{(Eq. 4.4)}$$

$$\text{NPV} = \sum_{t=0}^{n} [\frac{Benefit_{year}(\text{t})}{(1+\text{r})^{\text{t}}}] \qquad \text{(Eq. 4.5)}$$

With

$Benefit_{year}$ = yearly benefit [EUR/year]
B_{SRA} = total benefit (saved cost) [EUR/year]
$C_{SRA,\ yearly}$ = yearly maintenance cost of the SRA [EUR/year]

$Benefit_{year}$ (t) = net benefit in year t [EUR]
t = year
r = discounting factor (4%)
n = maximum life span of the investment in the SRA (10 years in this case)
NPV = net present value [EUR]

If the benefits of the SRA are larger than the cost of maintaining the SRA, a positive total net benefit can be obtained. Therefore, it can be concluded that it is possible to set up an SRA.

4.4. Data collection

This section describes and presents the data collected from the five different ports. The five considered SRA ports provided data concerning the number of vessels calling at their ports. For each of these vessels, the previous port is known and the type and size of the vessel [22].

4.4.1. Data for small vessels sailing entirely in the SRA

Based on the typology made in Figure 4.3, the number of vessels calling at an SRA port with a previous call in a foreign SRA port is counted. These values are shown in Table 4.12, along with the total number of vessel calls and the relative share of vessels sailing purely in the SRA to the total number of ships calling at the respective ports.

Table 4. 12: Number of small vessels calling at an SRA port with a previous port call in another country

Port	Number of small vessels only in SRA	Total number of vessel calls	Share SRA vessels relative to the total number of calls
Antwerp	29	14,191	0.20%
Zeebrugge	82	8,378	0.98%
Ostend	137	18,588	0.74%
Rotterdam	62s	30,588	0.20%
Vlissingen/Terneuzen	106	7,915	1.34%

Source: Own composition based on the port of Antwerp Authority (2018), the port of Oostende (2018), the port of Rotterdam Authority (2018), the port of Zeebrugge Authority (2018), Zeeland Seaports (2018).

From Table 4.12, it can be seen that there are only very few vessels that sail purely in the SRA. Most of the ships sailing in the SRA and coming from a foreign port are pilot vessels and tugboats. It is especially the case for the port of Ostend and Zeeland Seaports. Also, the relative share is minor for the total number of vessels calling at the five ports. It is an indication that the total percentage of BW consumed for these vessels is small.

[22] If the size of the vessel was not directly given in gross ton (GT) or DWT, these values were obtained via either estimations of the length of the ship or, if only the name were known, the GT and DWT values were collected by making use of Marine Traffic. https://www.marinetraffic.com.

4.4.2. Data for vessels using shore-based systems

The number of vessels using shore-based systems to treat the BW is calculated based on the same data sources. The results are plotted in Table 4.13.

Table 4. 13: Number of vessels, which would make use of a shore-based BW system, calling at an SRA port with a previous port call in another country within SRA

Vessel type	Size of the vessel	Ports				
		Rotterdam	Zeeland seaports	Antwerp	Zeebrugge	Ostend
Product tanker	<60,000 dwt	698	538	14	282	0
Handy size	<35,000 dwt	8	15	12	0	0
Small feeder	<1,000 TEU	63	18	51	0	0
Feeder	<2,000 TEU	97	1	31	0	0
Feeder max	<3,000 TEU	102	4	181	3	0
General cargo	All types	146	164	226	51	6
Gas carriers	All types	0	75	1	20	0
Chemical tankers	All types	13	169	492	3	6

Source: Own composition based on the port of Antwerp Authority (2018), the port of Oostende (2018), the port of Rotterdam Authority (2018), the port of Zeebrugge Authority (2018), Zeeland Seaports (2018)

Based on the obtained data and explained equations, the total benefit of vessels sailing in the SRA and the total net benefit of the SRA are computed. The following section analyzes the results in detail.

4.5. Results

The applied method and data collection results are built from three different perspectives. First, the benefits of the vessels navigating only in the SRA are discussed. Second, the benefits of the ships between foreign SRA ports (sailing partly in the SRA) that would use shore-based BW systems are explained. Third, the total net benefits of the SRA are given based on sensitivity analysis for specific input parameters.

4.5.1. Benefits of vessels sailing entirely in the SRA

The benefits of introducing an SRA for vessels purely sailing in an SRA are estimated to be zero. Most vessels navigating only in the SRA do not have any or very limited amounts of BW, considered mainly service vessels such as tug boats, pilot boats, and special purpose vessels. Secondly, the relative share in the total number of such ships calling at the different ports is minimal. Therefore, having an SRA is no benefit for these vessel types. Furthermore, for these vessels, there is no cost of installation of a BWTS.

4.5.2. Benefits of vessels sailing partially in the SRA

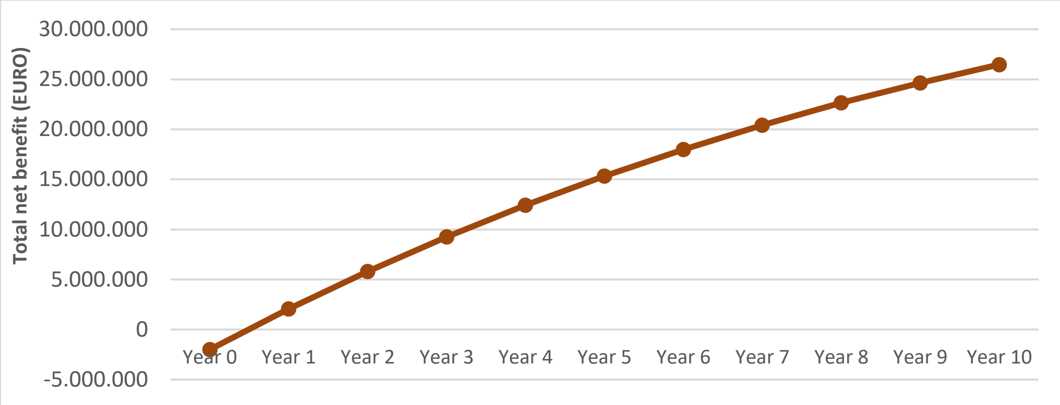
For all the vessel types sailing between foreign SRA ports and which will use shore-based BW systems, the benefits (saved cost of not using the shore-based system) are calculated [23] and shown in detail in Appendix A. Table 4.14 plots the overall benefits of each port within the SRA. As can be seen, the total benefit by setting up an SRA for all the vessels calling at Dutch ports (€3,051,681) is higher than the total benefit for the vessels calling at the Belgian ports (€1,285,440).

4.5.3. Total net benefits of the SRA

The total net benefit of the SRA is calculated with equation 4. For the cost of the SRA, there is an initial introduction cost of €2,000,000 at year 0 for the total SRA. The yearly maintenance cost of the total SRA is €200,000 per year. This estimation includes all the costs for the preparatory meetings, papers, regulations, invasive species monitoring according to OSPAR HELCOM protocol, reporting, and emergencies, including the required personnel. The yearly discounted net benefits of the SRA are given in Figure 4.4.

[23] For the calculation, it is assumed that the total port time of a vessel, using a shore-based BW system, is not affected.

Figure 4. 4: Yearly discounted net benefits (EUR)



After ten years, the total net benefit is €26,469,465, which means that it is economically worthwhile to introduce the SRA based on the assumed cost. The calculations index the yearly cost by 2% to cover inflation. The annual benefits are taken as constant[24]. Table 4.14 gives the total benefits per year for the fixed handling cost of shore-based BW (7.5 EUR/ton) for all five ports.

Table 4. 14: Total yearly benefit of the SRA based on Handling cost of [7.5 EUR/ton]

Port	Rotterdam	Zeeland Seaports	Antwerp	Zeebrugge	Ostend	Total value
Total benefits [EUR/year]	1,715,164	1,336,517	680,496	600,909	4,035	**4,337,122**

The total estimated benefit of the SRA is €4,337,122 per year. It means that for the given cost of installing the SRA and the given cost saving per ton ballast (€7.5), there is an economic benefit of installing the SRA.

[24] Due to the fact that no forecasts are available for the number of vessels calling at the different SRA ports, the yearly benefits are assumed to be constant.

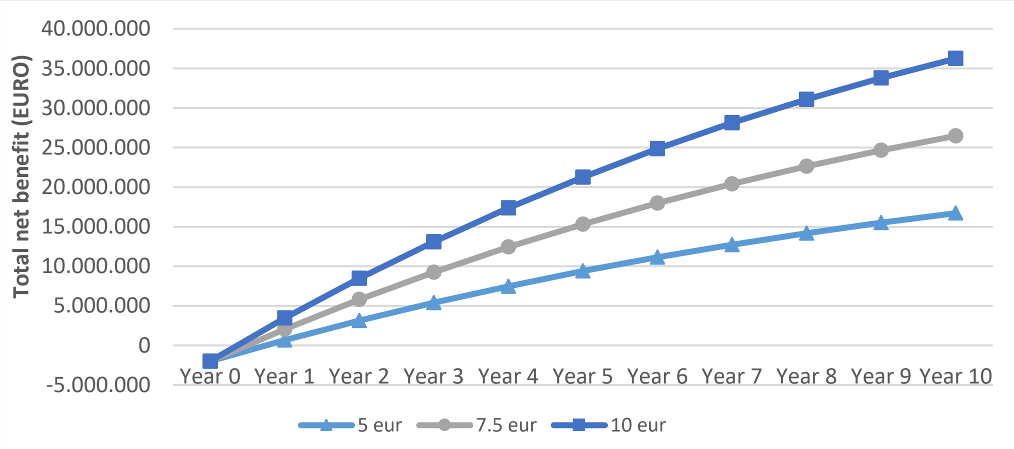
4.5.4. Sensitivity analysis

The sensitivity analysis in this research includes three parts. First, the outcomes of applying various handling costs for the BWTS are assessed. Second, the sensitivity concerning investment and yearly maintenance costs is evaluated. Third, the results corresponding to the change in the BW discharge volume are estimated.

Sensitivity analysis of handling cost

A sensitivity analysis is performed to appraise the effect of applying different handling costs for BW treatment. A variation is considered between 5 [EUR/ton], 7.5 [EUR/ton] and 10 [EUR/ton]. Figure 4.5 plots the impact of using a different cost to treat BW.

Figure 4. 5: Impact of varying cost for handling water ballast with shore-based systems (EUR)



It can be observed that for a lower cost for treating the BW, a lower net benefit after ten years (€16,702,785) is obtained. While, for a higher handling cost, the net benefits will be higher (€36,236,146). Moreover, the total yearly benefit of having the SRA is computed for all the ports in sensitivity analysis and plotted in Table 4.15.

Table 4. 15: Total yearly benefit of the SRA based on different costs to treat BW with a shore-based system

Port	Total benefits per year [EUR]		
	Handling cost of [5 EUR/ton]	Handling cost of [7.5 EUR/ton]	Handling cost of [10 EUR/ton]
Rotterdam	1,143,443	1,715,164	2,286,885
Zeeland Seaports	891,012	1,336,517	1,782,023
Antwerp	453,664	680,496	907,328
Zeebrugge	400,606	600,909	801,213
Ostend	2,690	4,035	5,380
Total value	**2,891,415**	**4,337,122**	**5,782,829**

As can be seen from the results, the total benefits of the SRA range from approximately €2,891,000 to €5,782,000 per year. The benefits are determined by the cost savings for vessel owners not needing to use the shore-based systems in the respective ports. The most significant part of these cost savings is obtained by vessel owners calling in Rotterdam. It means that there are more vessels, which most likely will be making use of shore-based systems, sailing from a Belgian port to the port of Rotterdam. The benefits for the vessel owners at the ports of Zeeland Seaports, Antwerp, and Zeebrugge are roughly the same. However, the potential benefits obtained in the port of Ostend are negligible.

Sensitivity analysis of investment and maintenance cost

The sensitivity analysis concerning the SRA cost depends on both the investment cost and the yearly maintenance cost. Table 4.16 reports the results of the net benefits for varying values of investment and annual maintenance costs.

Table 4. 16: Impact of SRA cost changes on net benefits

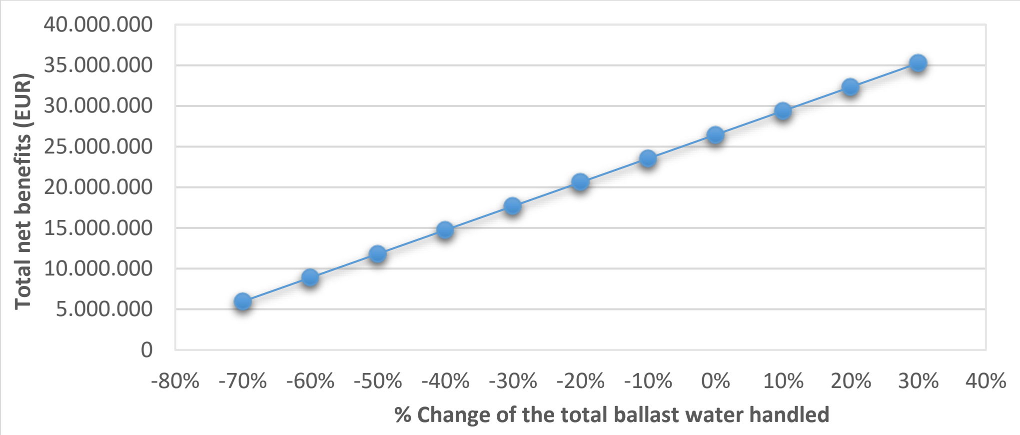
Investment cost of SRA [EUR]	The yearly maintenance cost of SRA [EUR/year]						
	200,000	500,000	2,000,000	2,500,000	3,000,000	3,500,000	4,000,000
500,000	27,482,812	25,263,640	14,167,781	10,469,161	6,770,542	3,071,922	-626,697
1,000,000	27,145,029	24,925,858	13,829,999	10,131,379	6,432,760	2,734,140	-964,479
2,000,000	26,469,465	24,250,294	13,154,435	9,455,815	5,757,196	2,058,576	-1,640,044
4,000,000	25,118,337	22,899,165	11,803,306	8,104,687	4,406,067	707,448	-2,991,172
5,000,000	24,442,773	22,223,601	11,127,742	7,429,123	3,730,503	31,884	-3,666,736
6,000,000	23,767,209	21,548,037	11,803,306	6,753,559	3,054,939	-643,681	-4,342,300
8,000,000	22,416,080	20,196,909	9,101,050	5,402,430	1,703,811	-1,994,809	-5,693,429
10,000,000	21,064,952	18,845,780	7,749,921	4,051,302	352,682	-3,345,937	-7,044,557

It can be concluded that the net benefits are above zero as the yearly maintenance cost is less than €4,000,000 per year and the investment cost is less than €5,000,000. These two values can be interpreted as the maximum values of the establishment and yearly maintenance cost for the SRA.

Sensitivity analysis of change in ballast water discharge volume

Several reasons can be considered to change the BW consumed. It can either be caused by an increase in the number of vessels, which will use shore-based systems to process BW, calling at the SRA ports, or by a change in BW consumption of the considered vessels. The difference in BW volume will impact the net benefit of the SRA. Figure 4.6 shows the impact of a percentage change in ballast volume handled in the considered SRA ports with an SRA investment cost of €2,000,000, a yearly maintenance cost of €200,000, and a BW treatment cost of 7.5 Euro/ton.

Figure 4. 6: Impact of a change in BW volume on the overall net benefit (Euro)



If the total volume of handled BW increases, the net benefits increase from €26,469,000 in the base case scenario to €35,259,000 if the incremental BW volume increases by 30%. However, for a decrease of 70% of the BW, the net benefits will decrease to €5,959,000.

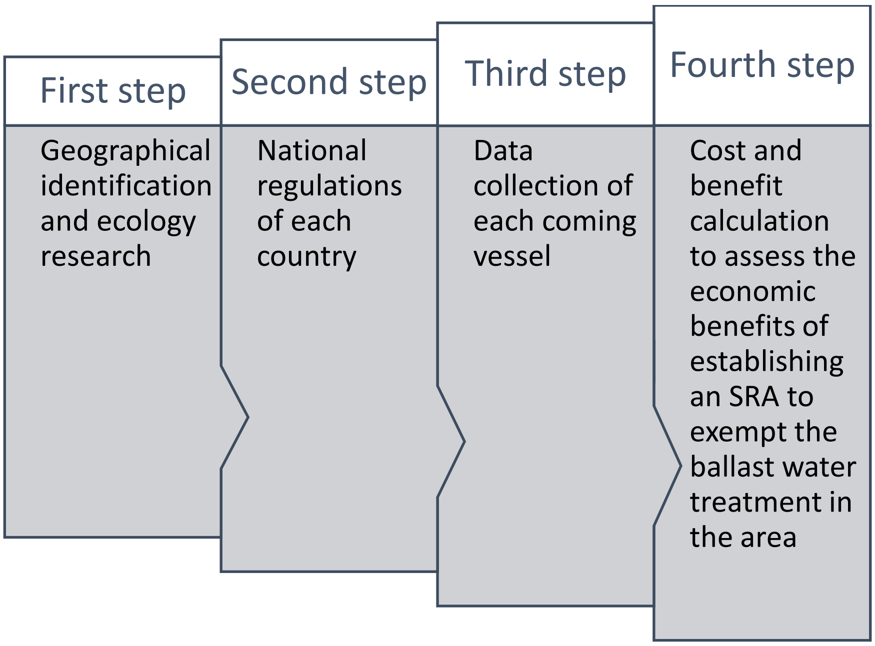
Based on the results, it can be concluded that on average, for a 1% increase in handled BW volume, the net benefits will increase by €293,000 (or vice versa). Furthermore, even with a decrease of 70% of the BW volume in 2017, a net benefit still can be obtained, and the SRA is economically viable.

4.6. Generalization and application to other ports/regions

Several remarks should be considered to extend this chapter's concept and methodology to other regions in the world, which is plotted in Figure 4.7.

- First, the chosen ports need to be in the same geographical area; in other words, the ports located in the neighboring countries should be selected. The decisive factor of this issue is based on ecological research, which requires to be performed to figure out the spread of local species in each region.
- Second, the local regulations of each country should be considered. Taking Australia as an example, it is not allowed to treat any ballast water in the domestic ports.
- Third, extensive data should be gathered, such as the type and size of ships calling at each port, the prior port of call for each vessel, and the yearly amount of ballast water consumption of each vessel.
- The fourth step obtains the total net benefit by estimating the cost and potential benefit of establishing an SRA.

Figure 4. 7: Generalization steps



Then, based on the type, size, and annual ballast water consumption. Finally, the benefits of ships sailing within the SRA are obtained based on Eq. 4.2, Eq. 4.3, Eq. 4.4 equations.

The benefit for small vessels will be the reduced operational costs of not needing to employ a shore-based system.

4.7. Conclusion

BW treatment is vital if the vessels sail internationally and no SRA is defined according to the BWM Convention. An SRA is determined as an area where BW treatment can be exempted, and it can be loaded and unloaded anywhere within this SRA in which there is a lower, or no, ecologic risk that potentially could be a threat to the native species.
There is a confrontation between the ecological and economic motives of establishing an SRA. However, in this chapter, the objective was not to assess the confrontation between economy and ecology. Still, the purpose was to develop a method that allows quantifying the economic viability of an SRA under the condition that all the ecological requirements are fulfilled in the North Sea between the Netherlands and Belgium.

This study provided an overview of the economic effects of an SRA exemption from the BWM in the region. The main objective of this research is to analyze the economic costs and benefits of an SRA surrounding the five ports within the Netherlands and Belgium, namely Rotterdam, Zeeland Seaport, Antwerp, Zeebrugge, and Ostend.

This chapter answered three research questions : (i) which ports and shipping routes can be selected and why? (ii) which vessel types and ship sizes are affected? and (iii) what are the costs and benefits of having an SRA? in particular, what is the benefit for vessel owners of using an SRA?

Two neighboring countries, i.e., the Netherlands and Belgium, are considered to reply to the first question. The significant seaports in these countries were selected as they play an essential role in the MarSC from a national and international perspective. The second question was responded to by providing a diagram of the typology of vessels based on their types and the maximum annual BW consumption. To answer the third question, a methodology is developed based on the cost and benefit of introducing an SRA, which provides the total net benefit for the vessel owners.

Based on the obtained results of the calculation of costs and benefits of the SRA, it is concluded that the total benefit for the vessels only navigating in the SRA is insignificant because these vessels carry a minor amount of BW. Besides, the relative share of these vessels compared to the total number of ships calling at the different ports is minor. For the vessels sailing partially in the SRA (the vessels navigating between foreign SRA ports), the results show that total benefits for all types of ships calling at the Dutch SRA ports (Rotterdam and Zeeland seaports) are higher than all the vessel types calling at the Belgian ports (Antwerp, Zeebrugge, and Ostend).

The total estimated benefit of the SRA (the sum of Dutch and Belgian ports) is €4,337,122 per year. After ten years, the total net benefit ascertains that it is economically worthwhile to introduce the SRA based on the assumed costs of investment, maintenance, and handling of a shore-based BWTS.

Three cases of sensitivity analysis were performed in this research, namely variation in the handling costs for the BWTS; alteration of investment and yearly maintenance costs; and change in BW discharge volume.

The results present that for a lower handling cost of the BW treatment, a lower net benefit is observed while, by increasing the handling cost, the net benefits will grow.

Furthermore, It is derived that the peak rates of the investment cost and yearly maintenance cost for obtaining the positive net benefits of the SRA are €5,000,000 and €4,000,000, respectively.

By altering the BW amount, it is observed that with a 1% increment in the treated amount of BW, net benefits will increase by €293,000. Moreover, by reducing this volume to 70% of the BW volume in 2017, the establishment of the SRA is still economically viable.

Chapter 5: Economic evaluation of alternative technologies to mitigate sulfur emissions in maritime container transport from both the vessel owner and shipper perspective

5.1. Introduction

The transport sector is one of the biggest energy consumers, resulting in over 26.6% of total energy consumption globally and 33% in Europe, and as a result, it is one of the biggest air polluters with a continuing growth projected by the European Commission (Žaglinskis et al. 2018). Emissions from the marine transport sector contribute significantly to air pollution and climate change (Moreno-Gutiérrez et al. 2015). Maritime shipping is considered a significant source of CO_2 emissions (Corbett et al. 2009; Dai, Fu, Yip, Hu, & Wang, 2018; Psaraftis & Kontovas, 2010; Schwartz et al. 2020; Sheng, Li, Fu, & Gillen, 2017; hung Lai et al. 2013).

Shipping is estimated to cause about 3% of the total global carbon emissions (European Commission, 2013; Smith et al. 2014; Kitada and Ölçer 2015; Dai et al. 2018; Schwartz et al. 2020). Besides, international marine shipping is a significant contributor to nitrogen oxide (NO_x) and sulfur oxide (SO_x) emissions, representing a share of 13% and 12% of global emissions, respectively (IPCC, 2013; Stevens et al. 2015). Different international organizations (i.e., IMO) and institution policies impose international environmental standards on their member states to limit the emission of greenhouse gases (Sys et al. 2015) as international maritime legislation is shifting towards lower levels of permitted exhaust gas sulfur oxide emissions from ships (Lahtinen, 2016). The current and possible future US, European, and Asian ECA zones are plotted in Figure 5.1.

Figure 5. 1: Existing SECA and NECA and future ECA

Source: MAN Diesel & Turbo 2016

New and existing regulations derived from the International Convention for the Prevention of Pollution from Ships (MARPOL) affecting the SO_x emissions from ships are summarized in Table 5.1.

Table 5. 1: MARPOL Annex VI marine SO_x emission reduction areas with fuel sulfur limits

Sulfur ECAs	Year	Fuel sulfur (%)	Fuel sulfur (ppm)
North Sea, English Channel	Before 2015	1	10,000
	As of 2015	0.1	1,000
Baltic Sea	Before 2015	1	10,000
	As of 2015	0.1	1,000
United States, Canada	Before 2012	1	10,000
	As of 2015	0.1	1,000
Global	Before 2020	3.5	35,000
	As of 2020	0.5	5,000

Source: Own composition based on (IMO, 2011; McGill, Remley, & Winther, 2013)

Also, to meet the fuel sulfur limits in Table 5.1, ships operating in the ECA areas must respect the MARPOL Annex VI Marine Tier III NO_x limits in 2016. Table 5.2 shows the applicable NO_x limits for ships and the dates they became or will become effective. (IMO 2011; McGill et al. 2013; Perera and Mo 2016).

Table 5. 2: MARPOL Annex VI NO_x emission limits

		NO_x limit		
Year	**Tier**	**n < 130**	**130 ≤ n < 2000**	**n ≥ 2000**
2000	Tier I	17 g/kWh	45 $n^{-0.2}$ g/kWh	9.8 g/kWh
2011	Tier II	14.4 g/kWh	44 $n^{-0.23}$ g/kWh	7.7 g/kWh
2016 *	Tier III	3.4 g/kWh	9 $n^{-0.2}$ g/kWh	1.96 g/kWh

*In NO_x ECAs (Tier II standards apply outside ECA's)

Source: Own composition based on (IMO 2011 and McGill et al. 2013)

The legislation values rely on the rated engine speeds (n) given in RPM (revolution per minute). From Table 5.2, Tier I and Tier II limits are global, whereas Tier III standards apply only in the NO_x ECA's (IMO 2011; McGill et al. 2013). Furthermore, progressive reductions in NO_x emissions from ships with marine diesel engines operating in ECAs by applying the three-tiered approach depend on the engine's age and maximum operating speed (Walker, 2016).

The Fourth IMO GHG Study 2020 estimated that total shipping emitted 1,056 million tonnes of CO_2 in 2018, accounting for about 2.89% of the total global anthropogenic CO_2 emissions in the same year. In 2012, 962 million tonnes were CO_2 emissions, while in 2018, this amount grew by 9.3% to 1,056 million tonnes of CO_2 emissions. IMO's MEPC has given extensive consideration to controlling GHG emissions from ships and adopted in 2011 a package of technical measures for new ships and operational reduction measures for all ships. Chapter four of MARPOL Annex VI, entitled "Regulations on energy efficiency for ships," is composed of two primary actions: the Energy Efficiency Design Index (EEDI) mandatory for new ships, and the Ship Energy Efficiency Management Plan (SEEMP).

Table 5. 3: Measures for GHG emission reduction

Measures to reduce GHG emissions		
Energy Efficiency Design Index (EEDI)	A technical measure of GHG emissions reduction - an estimate on the amount of CO_2 emitted by a ship for one unit of cargo carried	They are applied to new building orders from January 1, 2013. The primary purpose is to encourage the development of more efficient engines and vessels and compare CO_2 emission characteristics in terms of vessel size [25].
Energy Efficiency Operational Indicator (EEOI) and the Ship Energy Efficiency Management Plan (SEEMP)	An operational measure of GHG mitigation, including speed optimization, optimized routing, improved fleet planning, efficient supply chain management, network design, may impact logistics-based measures	They are applied to existing and new ships. The SEEMP refers to all GT 400 tons or more ships from January 1, 2013. The aim is to improve the energy efficiency of shipping operations and reduce GHG emissions. The EEOI is used as a tool to monitor the operational status of vessels and is based on the content of the SEEMP. The EEOI is a recommendation and not a mandatory monitoring tool of the SEEMP.
Market-based measures (MBMs)	Considers the carbon market, such as the emissions trading system, in terms of complementary technical and operational measures	The purpose of MBMs is to offset any increase in ships' GHG emissions, provide financial support through incentives for high-efficiency shipbuilding and operations, and reduce and adapt to climate change in developing countries. The basic idea of MBMs is to give incentives to low-carbon-emitting ships and penalize high-carbon-emitting vessels.

Source: Authors' composition based on Psaraftis and Kontovas 2010; Zheng et al. 2013; IMO 2016; Psaraftis 2016; Lee and Nam 2017

In 2018, IMO adopted an *initial strategy* on the reduction of GHG emissions from ships, setting out a vision that confirms IMO's commitment to reducing GHG emissions from international shipping and identifies levels of ambition as follows:

[25] All ships will have to calculate their Energy Efficiency Existing Ship Index (EEXI) following technical means to improve their energy efficiency and to establish their annual operational carbon intensity indicator (CII) and CII rating. The requirements for EEXI and CII certification are expected to come into effect from 1 January 2023.

Figure 5. 2: Initial strategy on GHG emissions

Carbon intensity of the ship to decline through implementation of further phases of the energy efficiency design index (EEDI) for new ships	To review with the aim to strengthen the energy efficiency design requirements for ships with the percentage improvement for each phase to be determined for each ship type, as appropriate
Carbon intensity of international shipping to decline	To reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008
GHG emissions from international shipping to peak and decline	To peak GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out as called for in the Vision as a point on a pathway of CO_2 emissions reduction consistent with the Paris Agreement temperature goals

Source: Author's composition based on *https://www.imo.org/en/OurWork/Environment/Pages/GHG-Emissions.aspx*

The IMO GHG Strategy provides a comprehensive list of candidate short-term, mid-term, and long-term measures, including, for example, further improvement of the EEDI and the SEEMP, National Action Plans, enhanced technical cooperation, port activities, research and development, support to the effective uptake of alternative low-carbon and zero-carbon fuels, innovative emission reduction mechanisms, etc.

As the significance of the reduction of ship emissions in ECAs has been highlighted, which necessitates ship owners and shipping lines to respect the regulations, the primary purpose of this research is to determine which of all the available options comply with the ECA regulation is economically most suitable for the vessel owner and the shipper. The research questions that will be investigated are:

- *According to the literature, what are the best alternative options to comply with the ECA regulation?*
- *Of those selected technologies, what are the maritime costs from a vessel owner's point of view, and what is the impact of the technologies on the generalized chain cost*?

A two-step approach is used to answer these two research questions. In the first step, an extensive literature study is conducted to determine which alternatives are the most suitable to use. The performed literature review will reveal the existing gap in the field, and consequently, this chapter attempts to move forward the research by covering the gap and providing new results.

In the second step, a cost modeling approach is applied for the selected alternatives based on van Hassel et al. (2016a, 2016b) (see chapter 3). This analysis uses a model designed for calculating the total vessel owner cost and the generalized cost of transporting a container from an origin to a destination. To achieve the objectives of this chapter, some adjustments need to be considered, and new parameters will be incorporated into the model. As the primary outcome of this stage, the best economical option both from the vessel owner's and cargo owner's perspective is suggested.

This research considers three alternative fuels or technologies: MDO, LNG, and scrubber technology. The reasons are three folds. Emissions from ships illustrate the steady rising trend from the year 2000 to 2020, in which the emissions of NO_x and SO_2 from ships increased by approximately 40%. By 2030, it is expected that the emissions of NO_x and SO_2 from ships will continue to increase by 35% and 32%, respectively (Deng et al. 2021). Thus, the importance of using alternative fuels to mitigate SO_x and NO_x is a significant issue in maritime shipping.

The first reason for selecting LNG and scrubber systems is that LNG and scrubber systems are currently used and are in operation around the world. Since 2010, the number of vessels fueled by LNG has grown consistently by 20% and 40% yearly. At the start of 2020, there have been 175 LNG-fueled ships in operation, excluding the 600 strong LNG carrier fleet, the majority of which are LNG-fueled, and over 200 ships on order (sea-lng, 2021). On the other hand, while there were 255 vessels fitted with scrubbing systems in 2015, the number surpassed 4,000 units in 2020 (ICCT - International Council on Clean Transportation, 2021; Statista, 2021).

Secondly, as the objective of this chapter pertains to the economic estimation of alternative fuels for the reduction of sulfur emission in ECA, LNG, and scrubber systems comply with IMO ECA regulations as scrubbers reduce sulfur emission by more than 90%, PM emissions by 60-90% and the emission of NO_x is reduced by 10% or less (den Boer & Hoen, 2015). In addition, the use of LNG as ship fuel will reduce SO_x emissions by 90-95% (MAN Diesel & Turbo, 2011). Compared to traditional HFO, LNG represents a 25% reduction in CO_2 emissions, a 90% reduction in NO_x emissions, and a 100% reduction in sulfur (SO_2) and fine particle emissions (Elengy, 2021).

Thirdly, these alternative technologies have been addressed widely from an environmental perspective in the literature, and in some cases, economic assessments are examined as well but mainly from vessel owners' standpoint. Thus, this chapter compares the results of previous studies and, more importantly, as a novel study, it considers the shippers' perspective in the economic assessment of LNG and scrubber system by evaluating the generalized chain cost. The latter evaluation shows how alternative options will affect the generalized chain cost and which option will provide the lowest generalized chain cost, which affects the policymaking process and provides an excellent view for logistics operators to deploy the best alternative solutions.

Based on alternative fuel used inside and outside ECA's, three diverse scenarios are discussed with two different maritime routes: one from Asia to Europe and the second one from the US to Europe, with varying ship sizes for each maritime route. The main differences in the scenarios depend on the engine and fuel used inside and outside ECA zones.

This study encompasses economic, environmental, and social dimensions of MarSC sustainability, and it pertains to the UN SDG 9 "*to upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies.*"

This chapter is based on the published paper by Mohseni et al. (2019); however, it is updated with newer data and more detailed results, and more elaboration on the literature review and applied methodology.

The remainder of this chapter is organized as follows. The literature review is explained in section 5.2, while the applied methodology is described in section 5.3. Section 5.4 clarifies the input data and different research scenarios, while section 5.5 illustrates the obtained results and provides graphic demonstrations of the outcomes. Finally, section 5.6 elucidates the general conclusions and findings of this chapter.

5.2. Literature Review

Initially, a comprehensive literature review of all the possible available options to comply with ECA regulations is carried out. The same approach explained in Chapter 2 (Literature Review) is applied here; however, some new keywords are used, which are: ECA; alternative technologies for maritime shipping; green shipping; LNG as an alternative fuel; Scrubber system in marine shipping, economic comparison of alternative fuels; emission reduction in ECA. Furthermore, the snowballing technique was employed to detect the most relevant papers on the subject.
The literature review is structured into three sub-sections. Firstly, a review of all the possible alternative technologies and measures to mitigate emissions is provided. Here, the main focus will be on the ECA zones and sulfur reduction legislation; however, the options on GHG emissions, particularly CO_2 emission reduction, are also discussed. Secondly, the positive and negative features of different fuels and technologies such as LNG, MDO, scrubber system, slow steaming, etc., are analyzed. The third section describes a review of research groups on comparing technologies mainly from economic and environmental aspects of sustainability.

5.2.1. Alternative marine fuels, technologies, and measures

The use of HFO as a marine fuel poses serious environmental and economic impacts (Roy & Comer, 2017). In 2013, McGill et al. stated that a large part of the marine fuel consumption (approximately 77%) is of low-quality, low-price residual fuel, also known as HFO, which tends to be high in sulfur. Various alternative fuels and technologies are discussed in the literature to mitigate the environmental pollution of marine shipping both globally and in ECAs. Annex VI allows alternative compliance methods with equivalent reduction effects (Doudnikoff & Lacoste, 2014; Lindstad & Eskeland, 2016). According to Lister et al. (2015), maritime ship owners and charterers are reacting to green concerns with innovative management procedures and operational practices to lower the carbon emission of shipping vessels.

There are numerous technology-based approaches to improving vessel efficiency and reducing emissions, including propeller re-design, anti-fouling measures for hulls, and improved engine operations (Corbett et al. 2009). However, the limitations of these measures have led to discussions about the potential for behavioral changes (operational changes and demand management) to achieve mitigation targets more cost-effectively (Buhaug et al. 2009). By educating and training the crew on energy-efficient operations, it is possible to make significant savings in fuel consumption and reduce emissions (Jensen et al. 2018).

The alternative fuels that are most commonly considered today are LNG, Electricity, Biodiesel, and Methanol. Other fuels that could play a role in the future are Liquefied Petroleum Gas (LPG), Dimethyl Ether (DME), Biomethane, Synthetic fuels, Hydrogen (particularly for use in fuel cells), Hydrogenation-Derived Renewable Diesel (HDRD), and Pyrolysis Oil. Additionally, fuels such as Ultra-Low-Sulfur Diesel (ULSD) can be used to comply with the regulations and support the transition to alternative fuels (Moirangthem & Baxter, 2016). Gaseous fuels are divided into oil, industrial, and natural gas. According to the state, the gas is separated into LPG, Compressed Natural Gas (CNG), and LNG

(Žaglinskis et al. 2018). Each fuel has benefits and drawbacks, but fuel flexibility, the ability to convert an engine to use a different fuel, will play an important role (Haskell, 2021)

There are several ways shipping companies can achieve compliance with the ECA sulfur regulations; (i) to continue to operate on high sulfur fuel oil while installing a scrubber (ii) fuel switching such as marine gas oil (MGO), (iii) using LNG or methanol as an alternative fuel (Germanischer Lloyd and MAN, 2012; Kristensen, 2012; Møllenbach et al. 2012; Semolinos et al. 2013; Doudnikoff and Lacoste 2014; den Boer and Hoen 2015; Fagerholt and Psaraftis 2015; Lindstad and Eskeland 2016) and (iv) using MDO as a realistic alternative for vessel owners (Semolinos et al. 2013).

Hybrid vessels by combining more than one type of energy source offer a promising approach (Peter et al. 2014). Furthermore, nuclear power has been recognized as the most sustainable alternative energy source for shipping, followed by LNG and wind power besides solar power, biofuels, and hydrogen (Ren & Lützen, 2017). Garg and Kashav (2019) state that LNG or nuclear-powered vessels for reducing carbon footprint are expected to be the future trend. However, the NO_X reduction can be obtained using high-performance new generation engines (Adamo et al. 2014).

Similarly, Stevens et al. 2015 classify the alternative technologies to reduce the fuel consumption and to mitigate the emission into five main classes such as measures to adjust (i) the hull of the ship, (ii) the propulsion, (iii) the installed machinery, (iv) alternative energy sources in which the technical solutions such as wind propulsion (sails) and alternative fuel types (low-Sulfur and LNG) are categorized and (v) operation (and maintenance) of the ship. The authors reveal the importance of the bunker price on the cost-effectiveness of new technologies.

Ren and Lützen 2017 develop a multi-criteria decision-making method for alternative energy source selection under incomplete information conditions. Table 5.4 explains the fifteen criteria for the sustainability assessment of alternative energy sources for shipping.

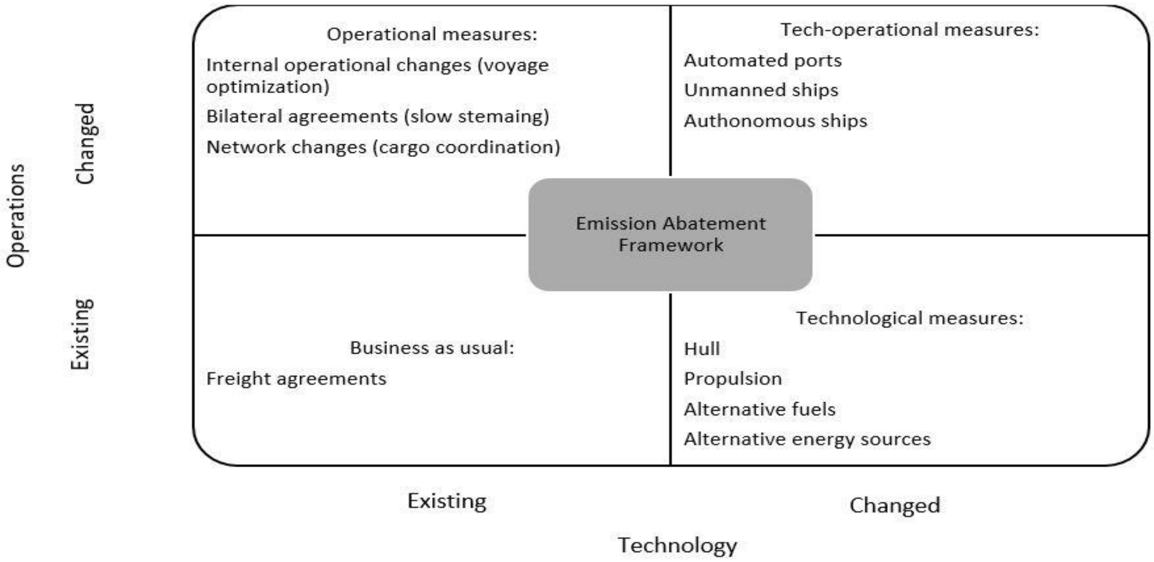
Table 5. 4: Four dimensions for sustainability measurement of alternative technologies

Dimensions for sustainability measurement	Criteria
Technological aspect	Maturity; Reliability; Energy storage efficiency
Economic aspect	Infrastructure; Capital cost; Bunker price; Repair and maintenance cost; Training cost and crew wage
Environmental aspect	SO_x reduction; NO_x reduction; GHG reduction; PM reduction
Social-political aspect	Social acceptability; Governmental support; Safety

Source: Authors' composition based on Ren and Lützen 2017

Based on the results, the technological aspect is regarded as the most important for selecting the alternative energy sources for shipping, followed by the environmental, economic, and - social-political aspects in descending order. Similarly, Schwartz et al. (2020) identify a hierarchy of ways to achieve emission reductions. The authors discuss three different kinds of operational solutions that can be used to reduce emissions, in addition to technological measures (Figure 5.3).

Figure 5. 3: Measures for emission reduction framework



Source: Authors' composition based on Schwartz et al. 2020

The authors demonstrate that a remarkable amount of emissions can be reduced by utilizing different technological and operational improvements, such as employing cargo coordination and slow steaming solutions. Furthermore, selecting the best option amongst alternatives and implementing it efficiently are the two essential phases towards achieving energy-efficient seaborne transportation (Kitada & Ölçer, 2015).

5.2.2. Advantages and disadvantages of alternative technologies

This section explains the current and available fuels' general definitions, benefits, and drawbacks. The objectives are first to provide a platform to understand each fuel/technology better and second to know which one can be most effective from the economic and compilation with ECA's regulations perspectives.
This chapter concentrates on sulfur emission reduction based on MARPOL Annex VI. However, it also sheds light on the IMO GHG Study considering reducing carbon emissions.

HFO

The generic term HFO describes fuels used to generate heat that have an exceptionally high viscosity and density, and it is a residual fuel incurred during the distillation of crude oil (Oiltanking 2021). The use of HFO as a marine fuel poses serious environmental and economic risks (Roy & Comer, 2017). In 2013, McGill et al. stated that a large part of the marine fuel consumption (approximately 77%) is of low-quality, low-price residual fuel, also known as HFO, which tends to be high in sulfur. However, HFO is less expensive than MGO and MDO, so it is still predominantly used in commercial shipping (Marquard & Bahls, 2021). HFO cannot generally be pumped at a temperature of 20°C and must therefore be preheated in the ship's tanks (Oiltanking 2021). Based on the regulations, HFO is not permitted to be burnt within ECAs unless an exhaust gas treatment system such as a scrubber is employed when the ships commute in these areas.

There are several HFOs in which the critical differentiator is the sulfur content. According to ISO 8217, High sulfur fuel oil (HSFO) has a maximum sulfur content of 3.5%, while Low sulfur fuel oil (LSFO) has a maximum sulfur content of 1.0% (Oiltanking 2021).

LNG

Natural gas reduces local air pollutants compared to traditional maritime fuels. Gaseous fuel available for marine use is natural gas that is very low in sulfur content and combusts lower NO_x, PM, and CO_2 (McGill et al. 2013). Among the technologies that are currently evaluated, the possibility for ships of switching to LNG as a primary fuel has raised significant concerns during the last few years (Chen, Zheng, & Zhang, 2018), and it is one of the options seen as an alternative fuel for deep sea, short sea, and inland navigation ships (Aronietis et al. 2015). LNG is considered one of the most promising marine alternative fuels due to its economic and environmentally friendly features (Deng et al. 2021). It is likely to be incentivized where economics favoring natural gas are coupled with air emissions public policy targets (Thomson et al. 2015). The general characteristics of LNG propulsion are critical to consider this option as a sustainable or transit solution for emission reduction. In the following part, some of the main positive and negative features of LNG propulsion are summarized according to different sources.

Table 5. 5: Advantages of LNG

	Advantage				
Reference	Availability	Cost	Availability of marine gas engines	Lower exhaust emissions	Energy density 60% of diesel
MAN Diesel & Turbo (2011)		x		x	
Kołwzan & Narewski (2012)	x	x		x	x
McGill et al. (2013)	x	x	x	x	
Stulgis et al. (2014)		x		x	
Aronietis et al. (2015)					
den Boer & Hoen (2015)			x		
Lindstad et al. (2015)		x			
Moirangthem & Baxter, (2016)	x				x
Bauen et al. (2017)				x	x
Žaglinskis et al. (2018)				x	x

Table 5. 6: Disadvantages of LNG

	Disadvantage					
Reference	Not compatible with existing engines	Requires space and adds weight	The future fuel price of LNG is uncertain	Limited bunkering infrastructure	Methane slip	Flammability and low freezing temperature
MAN Diesel & Turbo (2011)					x	
Kołwzan & Narewski (2012)						
McGill et al. (2013)	x	x		x	x	x
Stulgis et al. (2014)	x		x	x		
Aronietis et al. (2015)	x	x				
den Boer & Hoen (2015)			x			
Lindstad et al. (2015)	x	x			x	

Moirangthem & Baxter (2016)	x	x	x	x
Bauen et al. (2017)			x	
Žaglinskis et al. (2018)		x		

Source: Author’s composition based on the mentioned references

It can be observed from Tables 5.5 and 5.6 that the different advantages and disadvantages mentioned for LNG are not the same for all the papers, and it depends on the research conducted by each author. Moreover, cost competitiveness with distillate and residual fuels and energy density are other vital features of LNG.

LNG is a widely used alternative to liquid fossil fuels, but methane emissions reduce overall climate benefits (Hua et al. 2017; Balcombe et al. 2021).

Despite the positive impacts of LNG on sulfur emission reduction, there are a growing number of critics concerning the GHG reduction potential of LNG as an alternative for traditional fuels (Serra & Fancello, 2020). The methane slip emitted from gas and dual-fuel engines is essential to consider since it significantly impacts the global warming potential (IPCC, 2007, Brynolf et al. 2014). In addition, LNG engines cannot meet the industry’s 50% GHG emissions reduction target without further improvement. Improvements may come from reduced methane emissions, increased engine, and broader ship efficiencies, as well as a potential shift to low-carbon fuels (Balcombe et al. 2021).

While CO_2 emissions from LNG combustion are lower than emissions from HFO combustion, the fugitive emission of methane (a potent GHG) during bunkering or slippage in the engine dampens the GHG reduction potential (Bouman et al. 2017). Other negative aspects of LNG propulsion are categorized as the problem with compatibility with existing engines, which increases the operational and retrofit costs and requirements of more space and weight. LNG fuel tanks need two to three times the volume of fuel-oil tanks containing the same amount of energy (Serra & Fancello, 2020).

Moreover, ports must provide the necessary LNG bunker infrastructure if vessel owners switch to LNG. Port authorities, for their part, can only invest meaningfully in such facilities if they have a rough idea of potential demand for LNG bunkers from deep sea, shortsea and inland navigation, as LNG is increasingly substituted for HFO and MGO. Moreover, an essential aspect in the choice for LNG or low-sulfur fuel is the shipping companies' current day bunker strategies (Aronietis et al. 2017).

MDO

MDO generally describes marine fuels composed of various blends of distillates (live bunkers 2021). Marine diesel is similar to diesel fuel but has a higher density. Unlike HFO, MDO does not have to be heated during storage (Marquard & Bahls, 2021).
MDO is available with different sulfur content levels. For example, IFO 180 and IFO 380 can have a maximum sulfur content of 3.5%, according to ISO 8217 (live bunkers 2021).

MDO is sometimes also used synonymously with Intermediate Fuel Oil (IFO). In this case, the term MDO mainly refers to blends with a very small proportion of HFO. These variants are (i) MDO in general: a blend of distillates and HFO, (ii) MDO in a narrow sense: Blend of distillates and HFO, but with very low HFO content and (iii) IFO: Marine diesel with higher proportions of HFO (Marquard & Bahls, 2021). The different blending ratios make it possible to use MDO in many other engines (live bunkers 2021). However, concerning the price, MDO is more costly than HFO (Marquard & Bahls, 2021).

MGO

MGO usually consists of a blend of various distillates. MGO is similar to diesel fuel but has a higher density. Unlike HFO, MGO does not have to be heated during storage (Marquard & Bahls, 2021). Unlike HFO or MDO with a large proportion of HFO, MGO, which is based on the lighter distillates, has a low viscosity and can easily be pumped into the engine at around 20°C (Marquard & Bahls, 2021).
According to van Rynbach et al. (2018), the most straightforward option for meeting the upcoming low sulfur limits is to burn MGO with sulfur content at or below 0.1% in the ECA zones or 0.5% worldwide starting in 2020. Moreover, they state that this solution has no effect on the NO_x emissions and would require some additional technology to reduce NO_x for ships that have to meet Tier III levels. A negative aspect of MGO is the higher price compared to other fuels (Semolinos et al. 2013; Granskog 2015). The density of lighter fuels is lower than that of HFO and MDO, which may result in the amount of (lighter) fuel to the burner will differ from the amount original pre-set and thus cause ignition problems or increased smoke emission (live bunkers 2021).

Exhaust gas treatment systems

Another option to lower emissions and comply with regulations within ECA zones is by installing "scrubber" technology. Scrubbers allow ships in the ECA's to continue to burn traditional bunker fuel, yet still benefit from the savings created by the price difference between (cheaper) conventional bunker fuel and the low-sulfur diesel that would be required without scrubber technology (Stulgis et al. 2014; Lahtinen 2016). Since MGO is more expensive than HFO, scrubbers have received attention over the last years, and the number of scrubbers installed onboard ships has increased (den Boer & Hoen, 2015). In Table 5.7, the advantages and disadvantages of scrubber technology are reported according to different sources.

Table 5. 7: Advantages and disadvantages of scrubber technology

	McGill et al. 2013	Chryssakis et al. 2014	Stulgis et al. 2014	Aronietis et al. 2015	den Boer and Hoen, 2015	Van Rynbach et al. 2018
Advantages						
The possibility of using either low-sulfur or higher-sulfur fuels	x	x	x			x
Reduction of pollutants (PM, SO_x, and NO_x)	x		x	x	x	x

Disadvantages						
Loss of cargo capacity due to the size of the system	x					x
Increased cost		x	x			
Increased fuel consumption/power consumption		x	x	x	x	x
No reduction of CO_2 emissions			x		x	x
Additional GHG emissions					x	

Source: Author's composition based on (McGill et al. 2013; Chryssakis et al. 2014; Stulgis et al. 2014; Aronietis et al. 2015; den Boer & Hoen 2015; van Rynbach et al. 2018)

According to Table 5.7, reducing pollution is the main advantage most authors have. Scrubbers reduce sulfur emissions by more than 90%, PM emissions by 60-90%, and NO_x emissions by 10% or less (den Boer & Hoen, 2015). However, scrubbers have little effects on CO_2 emissions reduction. They increase energy consumption, estimated to increase fuel consumption by 3% in a seawater scrubber (open-loop) and 1% in a freshwater scrubber (closed-loop). Also, scrubbers increase GHG emissions by 1.5 to 3%.

CE Delft (an independent research and consultancy organization) published a new study that found that installing exhaust scrubbers on various vessels generates slightly lower CO_2 emissions than using very low sulfur fuel oil (VLSFO). Both strategies, however, result in an increase in CO_2 emissions from well to wake —the CO_2 emissions connected with an exhaust gas cleaning system range from 1.5 to 3%. The results show that, depending on the quality of the low-sulfur fuel, the refinery, and the crude oil slate, the emissions caused by generating low-sulfur fuels for these ships are often higher (Maritime Executive, 2020).

The negative characteristic of an open-loop system is its greater energy consumption than a closed-loop system, but there is no need for chemical additives like caustic soda in a closed-loop system. In the closed-loop scrubbers, no wash-water is produced that would have to be pumped into the sea (McGill et al. 2013; Aronietis et al. 2014; den Boer and Hoen 2015; Lahtinen 2016), and they retain the pollution onboard, but they are feasible only for short-distance travels (Serra & Fancello, 2020).

Concerns that open-loop scrubbers will clear air pollution at the cost of polluting the water have sparked a heated discussion. In 2019, the EU requested the IMO to evaluate its scrubber recommendations and adopt suitable actions, citing scientific evidence for the possible toxicity of water discharges (Serra & Fancello, 2020). There are four main principles of exhaust gas scrubbing systems: open-loop, closed-loop, dry and hybrid scrubbers. In Table 5.8, a brief description of each is reported.

Table 5. 8: Different scrubber systems and relevant features

Open-loop	Water and sulfur react to form sulfur acid, which is neutralized with alkaline components in the seawater. It typically uses seawater as the scrubbing medium and requires relatively large space on board.
Closed-loop	This type uses freshwater with an alkaline chemical (such as caustic soda). This type requires more space than open-loop systems.
Dry	It does not use any liquids in the process, but exhaust gases are cleaned with hydrated lime-treated granulates. The storage room has to be created onboard for granulate, which reduces cargo capacity. An advantage of a dry scrubber is its lower energy consumption compared to a wet scrubber.
Hybrid	It gives the possibility to either use a closed-loop or open-loop technology. Hybrid scrubbers are generally used as an open-loop system when the vessel operates in the open sea and a closed-loop system operating in harbor or estuaries, where water discharge is prohibited.

Source: Author's composition based on (McGill et al. 2013; Aronietis et al. 2014; den Boer & Hoen 2015; Lahtinen 2016)

Ammonia

Ammonia is an attractive option for the decarbonization of maritime shipping because of its relatively low GHG emissions, high energy density, competitive cost, and ubiquitous infrastructure for manufacturing, storage, and distribution (Al-Aboosi et al. 2021). Ammonia emits zero CO_2, SO_x, and close to zero NO_x. Unlike hydrogen, the deployment of ammonia as a marine fuel is still in the research and development phase as, to date, no ammonia-powered ship is operational (International Transport Forum - OECD, 2018).
A recently conducted survey by Lloyd's List reveals that the industry expects ammonia usage to grow to 7% of fuel by 2030 and 20% by 2050. As ammonia contains no carbon, it does not emit any CO_2 when fueling an internal combustion engine. It creates the potential for zero-carbon propulsion (Haskell, 2021). Further developments of ammonia as a complement or replacement for HFO can also offer a promising alternative to reduce CO_2 emissions long-term (International Transport Forum - OECD, 2018).

Ammonia volumetric energy density is similar to methanol and higher than hydrogen, making onboard storage economically feasible, albeit not as compact as the HFO used today (Haskell, 2021). Another advantage is that it can be stored at a temperature (-33.4 °C) that is easier to maintain than hydrogen (-252.9 °C). Moreover, it can be used in different ways, such as in diesel engines, fuel cells, gas turbines, etc., making it a very competitive option (International Transport Forum - OECD, 2018).

While ammonia is not highly flammable, concentrations in air as small as 0.25% can cause fatalities, making the fuel highly toxic to people. Handling onboard ammonia ships will require an entirely new set of skills and safety procedures. There is a need to understand the potential negative impacts on human lives, water, and soil in case of leakage or accidents and mitigate these types of risks. In addition, the combustion of ammonia in engines releases nitrous oxide (N_2O), a greenhouse gas even more potent than CO_2. Thereby, additional equipment will be required onboard to control NO_x emissions. Consequently, port authorities and regulators are presently reluctant to permit bunkering of ammonia due to toxicity hazards (Haskell, 2021). The use of ammonia as a marine fuel brings several technological challenges, and much work has to be done before NH3 engines are ready on the market (Serra & Fancello, 2020).

Hydrogen

Hydrogen is another potentially attractive and viable alternative fuel since it emits zero CO_2, zero SO_x, and only negligible amounts of NO_x. Hydrogen can be used as fuel in several different ways, such as in fuel cells, in a dual fuel mixture with conventional diesel fuels (HFO), and lastly, as a replacement for HFO for use in combustion machinery (International Transport Forum - OECD, 2018). Hansson et al. 2020 showed that hydrogen represents a more cost-effective marine fuel option than ammonia based on the energy system modeling to reach global GHG reduction in the long term.
However, the use of hydrogen fuel poses several challenges, including production, transportation, storage, related expenses, and safety issues (Saito, 2019; Serra & Fancello, 2020). In addition, there is no standardized design and fueling procedure for hydrogen-powered ships and their bunkering infrastructure (Lindstad et al. 2015). Furthermore, remaining safety design issues regarding the volatility of the fuel need to be resolved (International Transport Forum - OECD, 2018).

Moreover, hydrogen is difficult and costly to produce, transport, and store as a sustainable fuel. Special consideration has to be given to the storage of onboard hydrogen ships to ensure safe operations. Compressed hydrogen has a very low energy density by volume requiring six to seven times more storage space than HFO. On the other hand, liquefied hydrogen requires storage at very low temperatures (-253 ^{o}C), associated with significant energy losses and very well insulated fuel tanks. Thus, hydrogen storage tanks can also result in cargo space loss due to their size. These increased costs of the fuel and the currently limited gains in CO_2 emissions, combined with challenges regarding the storage of hydrogen, safety, and the cost of fuel cells, mean that hydrogen and fuel cells are unlikely to play a significant role in the propulsion of shipping in the next decade (TNO and TU Delft, 2017).

Methanol

Methanol could potentially improve air quality and GHG emissions from ships at a low cost (Balcombe et al. 2021). Compared with HFO, methanol has an emission reduction potential of 99% for SO_x, 60% for NO_x, and 95% for particle matter (PM) (International Transport Forum - OECD, 2018). Methanol has properties that are similar to those of methane when it is injected into an engine. Hence, methanol is also used in a dual-fuel concept (Moirangthem & Baxter, 2016). In addition, Methanol is convenient because it requires only minor modifications to ships and bunkering infrastructure since it is similar to current fuels in several respects and is generally safer than conventional fuels and LNG. (International Transport Forum, 2018).
Despite their high potential to cut CO_2 emissions, clean alternatives such as biofuels, methanol, and hydrogen are unlikely to become practical on a wide scale in the near future due to several technical, economic, and safety obstacles. The same applies to nuclear energy for ship propulsion (Serra & Fancello, 2020).

Slow Steaming

Slow steaming has been an interesting topic for scholars and has been implemented by most shipping lines and in recent years to assess its effects on CO_2 emission reduction, fuel consumption, and in general on maritime shipping. The continuous increase in marine fuel oil consumption, bunker price, and excess capacity available in the market bring the urgent need for ship liners to seek ways to minimize the use of fuel consumption (Cariou, 2011; Wong et al. 2015; Yang et al., 2013). Speed reductions may provide substantial energy savings due to the closed relationship between energy costs, speed reductions, and revenues (Corbett et al. 2009; Doudnikoff & Lacoste, 2014). Slow steaming practices aim at improving fuel technology efficiency on existing vessels (Jasmi & Fernando, 2018).

Various elements should be evaluated to employ slow steaming, such as cargo volume, cargo nature, delivery schedule, contract of carriage, and customer priorities (Wong et al. 2015). Furthermore, the long-term sustainability of slow steaming depends on the additional operational costs for the number of vessels added and on changes in inventory costs as containers spend more time at sea (Cariou, 2011). Chang and Wang (2014) propose that shippers must ensure that the adjusted speeds are sufficient to meet demand and alliances with other shipping companies to avoid having additional vessels and compensate for trade loss. The application of slow steaming brings positive and negative impacts on maritime shipping, as discussed in Table 5.9.

Table 5. 9: Comparison of positive and negative effects of slow steaming

Advantage of slow steaming	The disadvantage of slow steaming
Reduction of bunker cost and gas emission	If there is no sufficient idle capacity, slow steaming could extend a ship's voyage time
Improvement of the actual supply/demand balance	The lengthened voyage leads to higher operation cost
Decrease in the lay-up cost if there is idle capacity	The transit time for a voyage is extended, and the containers onboard will be occupied for a longer time, producing the inventory cost.
Absorption vessel overcapacity is an effective way to save fuel costs	More vessels need to be added to the service to keep the frequency of the liner service or the schedule.
Environmental benefits by lowering the carbon emission volume	Adverse impact on delivery schedule and quality services; time-sensitive cargos, e.g., reefer cargo with vegetables, seafood, fruits, medical suppliers.
Integration of the cost reduction initiatives from operations and the marine section as well as the commercial impact from the trade section	The impact on fuel consumption depends on the speed reduction.
The impact on fuel consumption depends on the speed reduction (due to the non-linear relationship between speed and fuel consumption).	Increase of cargo in-transit inventory costs due to the delay in the arrival of the cargo
Reduction of fuel consumption	Increasing preference for shippers to use land-based alternatives, mostly road, may increase overall GHG production.

Improvement the schedule timeliness	Conflict with the minimum safe power necessary for a ship to have in adverse weather conditions. In the short run, freight rates will go up once the overall transport supply is reduced due to slower speeds.

Source: Authors' composition based on Notteboom and Vernimmen 2009; Cariou 2011; Notteboom and Cariou 2009; Ronen 2011; Wang and Meng 2012; Maloni et al. 2013; C. C. Chang and Wang 2014; Doudnikoff and Lacoste 2014; Yin et al. 2014; Wong et al. 2015; Psaraftis 2016; Schwartz et al. 2020.

One of the main advantages of slow steaming is the reduction of CO_2 emission and its impact on fuel consumption. However, the extension of the transit time, which leads to more required vessels to maintain the planned frequency and increment in the ship's operational cost, is recognized as the most crucial barrier of slow steaming.

5.2.3. Economic and environmental comparison of alternative technologies

Based on the literature review, numerous sources compare available alternative technologies from different dimensions of sustainability. Hua et al. 2017 compare the difference of atmospheric emissions from HFO and LNG across the life-cycle assessment (LCA) and assess the global warming impact from these two fueling alternatives. The findings indicate a possible improvement in total fuel-life-cycle GHG emissions from LNG as an alternative fuel to power ships. Furthermore, a significant reduction in NO_x, SO_2, and PM10 is achieved from switching the fuel from HFO to LNG.

Ammar 2019 considers methanol as an alternative fuel for a Cellular container ship to comply with the IMO emission regulations and investigate the environmental and economic benefits of the methanol-diesel dual-fuel engine. Based on the results, from the ecological point of view, using a dual-fuel engine with 89% methanol and 11% MDO will lead to reductions in NO_x, SO_x, CO, CO_2, and PM emissions by 77%, 89%, 55%, 18%, and 82%, respectively and to reduce the dual-fuel cost to the cost of the diesel fuel at maximum continuous rating (MCR), the shipping speed should be reduced by 28%.

Table 5. 10: Studies on sustainability assessment of alternative technologies

Reference	Objectives
Man Diesel and Turbo 2011	To figure out if exhaust gas treatment systems are the preferred technical solution.
Aronietis et al. 2014	To select the best retrofit solutions.
Hsu et al. 2014	To assess the alternative solutions such as MGO, LNG, scrubber system, Methanol with three key elements: environmental, economic, and technical issues.
DNV GL and MAN Diesel & Turbo 2016	To analyze the costs and benefits of various fuel options for a case with one particular ship and its operating pattern
Fearnleys 2017	To compare different alternative shipping fuels.
Abadie et al. 2017	To examine the adaptation of the shipping sector to stricter emissions regulations by either fuel switching or installing a scrubber.
Corbett et al. 2009	To evaluate whether vessel speed reduction can be a potentially cost-effective CO_2 mitigation option for ships calling on US ports.
Psaraftis and Kontovas 2010	To examine whether speed reduction in SECA can work as a measure to reduce SO_x emissions.
Cariou 2011	To assess whether slow steaming is a sustainable means of reducing CO_2 emissions.
Cariou and Cheaitou 2012	To argue if a unilateral measure of a speed limit for all ships entering European Union (EU) ports can create a benefit to society without costing owners by using the example of CO_2 emissions generated by container vessels from Northern Europe to the East Coast of South America, and from Northern Europe to US East Coast/US Gulf/US West Coast.
Schinas and Stefanakos 2012	To provide a methodological framework for assessing the cost impact of environmental measurements and the increase of operating expenses of seagoing vessels due to the sulfur limits by MARPOL Annex VI.
Maloni et al. 2013	To clarify the costs and benefits of slow steaming across stakeholders (carriers and shippers) and the associated environmental impacts of a container lane between Asia and North America (Port of Los Angeles).
Norlund and Gribkovskaia 2013	To study emissions reduction in supply vessel operations by optimizing speed while planning vessel schedules and fleet size for a supply base.

Zheng et al. 2013	To investigate the impact of implementing the Energy Efficiency Design Index (EEDI) on the shipbuilding industry in China.
Acciaro 2014	To discuss the optimal time for investment in LNG retrofit.
Brynolf et al. 2014	To examine three different strategic options (i) HFO combined with Selective Catalytic Reduction (SCR) and an open-loop scrubber, (ii) MGO combined with SCR, and (iii) LNG for NO_x reduction emission in ECA.
C. C. Chang and Wang 2014	To develop a model to identify the optimum speed reduction strategy to minimize costs and mitigate CO_2 Emissions. The optimum speed reduction for four scenarios based on ship speed, fuel prices, and time charter rates are determined to maximize the speed reduction profit.
Doudnikoff and Lacoste 2014	To study speed reduction in SECA as a cost-minimizing behavior to save an expensive fuel required by regulation. From the container shipping industry perspective, examine the possible consequences of sulfur Emissions Control Areas (SECA) on vessel speed.
Jiang et al. 2014	To examine the costs and benefits of reduction measures such as sulfur scrubbers and MGO for the shipping industry to comply with the sulfur emission regulations.
Holmgren et al. 2014	To study and analyze the effects of the implementation of MARPOL Annex VI in the North and Baltic Sea SECA and the possibility of a modal shift to the road.
Y. T. Chang et al. 2014	To measure the emissions of noxious gases (NG), such as SO_2, NO_X, and PM, from vessel operations in a potential ECA.
Fagerholt and Psaraftis 2015	To consider two new speed optimization problems: 'Extension of Ronen's approach to ECAs' and 'ECA-refraction problem' for ships that use fuel switch and sail in and out of ECAs (deep-sea vessels).
Fagerholt et al. 2015	To develop an optimization model to be applied by ship operators in the case of ECAs to determine sailing paths and speeds that minimize operating costs for a ship.
Patricksson et al. 2015	To address fleet renewal issues related to emission regulation compliance with regional emission limitations related to sulfur emission regulations, particularly the potential challenge of so-called ECAs.
Sanchez Rodrigues et al. 2015	To examine sustainability issues for maritime operations in the UK by assessing total CO_2 emissions and costs of import re-routing containers.
Wong et al. 2015	To analyze slow steaming sustainability initiatives by considering fuel consumption, carbon emission, and on-time delivery in trans-pacific trade service routes from the east coast of the U.S. to the Asia Pacific in Southeast Asia by considering general cargo containers, reefer containers, and empty containers.
Lindstad and Eskeland 2016	To analyze risks following the IMO direction to extend locally and regionally motivated emissions regulations, i.e., North America and Northern Europe (ECAs).
Pettit et al. 2018	To investigate whether technological and operational innovations in shipping will result in a substantial and swift reduction in carbon emissions and the emergence of a new socio-technical regime in shipping.
Svindland 2018	To focus on the environmental effects of ECA in Northern Europe regulation on short sea shipping and to present SO_2 emission calculations of two container feeder vessels.
Schwartz et al. 2020	To analyze if it is economically feasible to cut down CO_2 emissions and improve the efficiency of the sea freight sector by investing in new technologies and operational measures in general cargo vessels operating in the Baltic sea.

Source: Author's composition based on the mentioned references

The above studies display the comparison of different alternative technologies from a ship-owner perspective. They compare the LNG propulsion by scrubber technology or options for specific ship types and maritime routes that benefit vessel owners. Although much study has been performed on the economic and environmental consequences of green practices and emission control on ship owners and shipping lines, this chapter shows that less attention was given to green practices and emission regulation impacts shippers and other stakeholders.

In this research, the objectives are not only an economic comparison of three different alternative fuel options from a vessel owner point of view but also an economic assessment of different options from a shipper perspective, which shows how alternative options will affect the generalized chain cost and which option provides the lowest generalized chain cost. The latter assessment contributes to policymaking and gives logistics operators a good overview of utilizing the best alternative options.

5.3. Methodology

The starting point for the analysis is the CCM, proposed by van Hassel et al. (2016a, 2016b) (see chapter 3) as the second step of the applied methodology. The model is further developed and adapted to address this chapter's specific research questions. The focus is on the economic evaluation of three different methods to comply with the standards of the ECA zones. This analysis will be done for both the chain and vessel owner costs. Therefore, given the specific objective of the present chapter, the base model needs to be adjusted. Firstly, the model has been extended to calculate the vessel owner cost. It means that the total cost for operating a container vessel can be calculated on a given loop. These costs include all the vessel-related costs such as running cost, voyage cost (including the cost in ports), and fixed cost. All these costs are calculated for a total round trip.

Secondly, more maritime distance data is collected from Marine Traffic (2018) containing the distance sailed in ECA zones. It means that this additional information is added for each port-to-port combination in the total maritime distance database in the model. The nautical distance database is an 80 by 80 matrix. Furthermore, 20 different container vessel sizes are included in the model, ranging from 500 TEU load capacity up to 20,000 TEU. The vessel data is collected from RINA (1992– 2016).

Based on this information, the fuel cost can be calculated when a vessel is sailing in ECA zones using either MDO, LNG, or HFO (including a scrubber).

The time that a vessel is sailing in ECA zones is determined by the vessel's speed and distance sailing in the ECA zones. The fuel consumption of the ship, using different measures to mitigate the ECA regulations, is then determined by the following formula.

$$FC_{Voyage,i} = FC_{ECA,i} + FC_{NONECA,i} \qquad \text{(Eq. 5.1)}$$

$FC_{Voyage,i}$ is the fuel cost for a voyage for vessel type *i*, while $FC_{ECA,i}$, and $FC_{NONECA,i}$ are the fuel costs for a journey in either ECA-zones or non-ECA-zones.

$$FC_{ECA,i} = \frac{D_{ECA}}{V_{Vessel,i}} . SFC_{i,j} . \frac{(\Delta_{Payload} + \Delta_{LW,i})^{2/3} . V_{Vessel,i}{}^{3}}{C_{\mathrm{admin,i}} . Pb_i} . FP_j \qquad \text{(Eq. 5.2)}$$

With:

D_{ECA} = the distance sailed in the ECA-zones (nm)
$V_{Vessel,i}$ = the speed of vessel type i (knots)
$SFC_{i,j}$ = the specific fuel consumption of the considered engine type or installation j (LNG, MDO or scrubbers) for vessel type i (tones/h)
The deltas represent the displacement of the vessel, both for the payload and the lightweight, and are expressed in cubic meters
Pb_i = the installed engine power (kW)
$C_{Admin,i}$ = the admiralty constant of vessel type i (kW/(kn^3.tonne$^{2/3}$)).
Including these elements in the model allows researching the effects of operational speed changes.
FP_j = the fuel price per ton for fuel type j (HFO, MDO, or LNG). For $FC_{NONECA,i}$ a similar equation is used only when the distance D_{nonECA} is used, which is the distance sailed on a specific trip between two ports that are not in the ECA-zones (nautical mile).

After applying the adjustments to the model, the following sections explain the scenarios and the input data that demanded the economic assessment of the three technologies.

5.4. Scenario Development

Different scenarios are developed to compare selected alternative technologies. Firstly, there is the reference scenario. This scenario equals the "business as usual" situation intending to provide a comparison reference for the modeled alternative scenarios. In the reference scenario, the vessel complies with the ECA regulation by using MDO fuel, while outside the ECA zones, the ship will use HFO. The alternative scenarios tested are explained in Table 5.11. Every scenario is a combination of input data that characterizes the investigated technology. These include associated investment costs and fuel cost impacts.

Table 5. 11: Different scenarios based on the type of engine

Scenario	Engine	Fuel used inside ECAs	Fuel used outside ECAs
Reference	Diesel Engine	MDO	HFO
LNG	Dual Engine	LNG	LNG
HFO + Scrubber	Diesel Engine	HFO with scrubber	HFO

The main differences in the scenarios depend on the engine and fuel used inside and outside ECA zones. The scenarios mentioned above are applied to two different routes. The first route is the trade lane from Far East Asia to Europe, while the second route focuses on the US to Europe, hence the Transatlantic route. For each route, different container vessel sizes are tested.

Table 5. 12: Ports in the loop of each route *

Loop	Ports in the loop	Vessel sizes (TEU)
Asia-Europe	Ningbo-Shanghai- Xiamen- Hong Kong- Yantian- Kelang- Tanger Med-Southampton-Hamburg-Bremerhafen-Zeebrugge Rotterdam- Le Havre-Marsaxlokk- Khor al Fakkan- Jebel Ali-Ningbo	9,115 13,892 18,800
US-Europe	Miami- Jacksonville- Savannah- Charleston- New York- Antwerpen- Bremerhafen- Rotterdam- Le Havre- New York-Norfolk- Charleston- Miami	4,600 5,466 9,115

* These routes are based on existing container loops

Furthermore, to assess the impact of the considered options from a MarSC point of view, firstly, a marine supply chain must be determined. The considered supply chains in the scenarios are given in Table 5.13.

Table 5. 13: Selected supply chains

Route	Origin	Destination
Asia - EU	Shanghai	Brussels, Munich, Berlin
US - EU	Jacksonville	Brussels, Munich, Berlin

In the Asia-EU trade route, the origin port is considered as Shanghai port as it is the most congested port in the world (Marine Insight, 2021), while in the US-EU trade route, the port of Jacksonville is the origin port as this port is the second most congested port in East Coast of the US. The model does calculate the generalized cost from Hinterlands Asia and the US to Hinterland Europe separately. In both routes, three cities are selected as destinations based on NUTS-2 regions in Europe.

In Europe Hinterland (final destination), five different ports in Hamburg – Le Havre range are taken into account. The model can estimate the generalized chain cost for each of the above cities in the NUTS-2 region, based on each port which means there are five various outcomes overall for each destination. Table 5.14 shows the Hamburg – Le Havre port ports and their relevant terminals.

Table 5. 14: Destination ports in Europe

Port in Europe Hinterland	Hamburg	Bremerhaven	Zeebrugge	Rotterdam	Le Havre
The terminal in each port	Container Terminal Hamburg (EUROGATE)	Eurogate	APMT	Maasvlakte I	TNMSC

5.4.1. Input Data

The model requires some data to quantify the fuel consumption by adding the aforementioned formula. To calculate the fuel consumption of each vessel type, the following Table is used to calculate HFO, MDO, and LNG fuel consumption.

Table 5. 15: Specific fuel oil consumption

Specific fuel oil consumption (typical for 52 MW engine)	
Type of fuel	Fuel consumption (kg/KWh)
HFO	0.18
MGO	0.18
LNG	0.13
Pilot fuel	0.02

Source: Own composition based on MAN Diesel and Turbo (2011)

Based on Table 5.15, the fuel consumption for LNG engines is determined as 0.15 kg/kWh. The LNG engine fuel consumption includes the direct fuel consumption of LNG (0.13 kg/kWh) and the pilot fuel consumption (0.02 kg/kWh). Moreover, for HFO and MDO, fuel consumption equals 0.18 kg/kWh.

Fuel consumption per hour can be determined based on the installed power and the vessel's design speed. Fuel consumption per hour (tons/hour) is obtained by multiplying fuel consumption for each fuel (kg/kWh) by the installed power of the vessel type (kW/1000). This calculation is reported in Table 5.16 for each fuel used and vessel. In the model, a 3% increase in fuel consumption is considered for the scrubber system: the use of a scrubber increases the energy consumption, which is calculated to raise fuel consumption by 3% in the case of seawater scrubber (open loop) and by 1% in case of freshwater scrubber (closed loop) (den Boer & Hoen, 2015).

Besides, 15% of the total fuel consumption of the main engine is considered to estimate the fuel consumption of auxiliary engines [26]. If the main engine is running on HFO or MDO, the fuel used of the auxiliary engine is considered as MDO, while LNG fuel is taken into account for the auxiliary engine if the main engine of the ship is using LNG.

Table 5. 16: Fuel consumption of vessels for different fuels

		Type of Engine				
		Main engine	Auxiliary engine	Main engine	Auxiliary engine	Main engine
		Fuel Used (tons/hour)				
Vessel size (TEU)	Installed power (kW)	**MDO**	**MDO**	**LNG**	**LNG**	**HFO with Scrubber**
4,600	36,560	6.58	0.99	5.48	0.82	6.78
5,466	24,680	4.44	0.67	3.70	0.56	4.58
9,115	41,400	7.45	1.12	6.21	0.93	7.68
13,892	62,030	11.17	1.67	9.30	1.40	11.50
18,800	61,000	10.98	1.65	9.15	1.37	11.31

Source: Own composition based on RINA (1992– 2016) and MAN Diesel & Turbo (2011)

[26] According to GloMEEP (2021), the auxiliary engines are used for electrical power production onboard and can represent up to 15% of the total fuel consumption for a vessel with diesel-mechanical.

Next to the adjustments to the fuel cost, some cost impacts are expected in the running cost of the container vessels, including crew cost, repair cost, maintenance cost, and insurance cost. According to MAN Diesel & Turbo (2011), using LNG as fuel, crew cost, maintenance, and repair cost increase by 10% compared to using MDO or HFO. While, by applying the scrubber scenario, crew cost, maintenance, and repair cost will rise by 20%.

In this model, the external costs of pollutants such as SO_x, NO_x, CO_2, and PM are considered to internalize the external costs. Table 5.17 reports the external costs of pollutants.

Table 5. 17: External costs of pollutants

Type of cost	Value (EUR/ton)
Cost SO_x	0.04
Cost NO_x	1328
Cost PM10	0.48
Cost CO_2	25

Source: van Essen et al. 2011

The following cost parameter is the purchase price of the ships. The data is obtained from the vessels in this study (Drewry, 2015). Furthermore, this capital cost must also include the investment of LNG propulsion (retrofit) or a scrubber system. According to Aronietis et al. (2015), the investment cost for LNG propulsion is provided within a range of €10 – €20 million, and for the scrubber system, this range is €2 – €4 million. In this study, the average investment/retrofitting cost is an approximation value and varies based on the vessel size. The capital cost of vessels is reported in Table 5.18.

Table 5. 18: Investment cost for LNG propulsion and scrubber system of ship types [EUR]

Vessel size (TEU)	Purchase cost	LNG retrofitting		Scrubber retrofitting	
		Average retrofitting cost of LNG *	The total capital cost of LNG	Average retrofitting cost of the scrubber *	The total capital cost of the scrubber
4,600	49,846,000	15,000,000	64,846,000	2,500,000	52,346,000
5,466	56,205,000	15,000,000	71,205,000	3,000,000	59,205,000
9,115	80,236,000	17,000,000	97,236,000	3,500,000	83,736,000
13,892	107,588,000	19,000,000	126,588,000	4,000,000	111,588,000
18,800	132,809,000	20,000,000	152,809,000	4,000,000	136,809,000

* An approximation value.

Source: Own composition based on Drewry 2015; Aronietis et al. (2015)

One of the essential cost parameters is voyage cost which includes the cost of applied fuel in each scenario. Data concerning the fuel cost is collected from Bunkerworld (2018). An average fuel cost of 400 EUR/ton for HFO, 494 EUR/ton for MDO, and 310 EUR/ton for LNG is assumed. All the values are expressed or converted in Euro for the model's convenience.

5.4.2. Sensitivity analysis

In this study, two different sensitivity analyses have been taken into account. Initially, to consider the effect of slow steaming on the results, % of design speed has been changed. By default, the ship's speed is considered 90% of the design speed of the vessel; however, in the sensitivity analyses, the ship's speed is reduced by 10% and 20%, respectively, and is selected as 80% and 70% of the vessel. It means that, for each vessel size, three different speeds (% of design speed of the vessel size (90%, 80%, and 70%)) are considered, resulting in 27 scenarios for each maritime route. Table 5.19 plots the design speed of the vessels.

Table 5. 19: Operational parameters of the vessels

Vessel size (TEU)	Design speed (knots)	Installed power (kW)	Average payload ship (% of payload)	Port approach speed (knots)	Speed in the port (knots)
4,600	22.5	36,560	80	10	5
5,466	21.73	24,680	80	10	5
9,115	22	41,400	80	10	5
13,892	22.69	62,030	80	10	5
18,800	21	61,000	80	10	5

Secondly, to figure out the effect of the fuel price in the calculation and realize how the maritime and chain costs are affected by changing the fuel price, the fuel price of MDO and LNG has been changed. The fuel cost of MDO is decreased to 425 (EUR/ton), which is a 13% reduction compared to base fuel price, while the fuel cost of LNG increases by 18% and reaches 380 (EUR/ton).

Table 5. 20: Alteration of fuel price

Type of fuel	Base fuel price [EUR/ton]	Fuel price in the sensitivity analysis	Alteration percentage
HFO	400	400	0%
MDO	494	425	-13%
LNG	310	380	+18%

5.5. Results

The adjusted CCM is applied to the scenarios mentioned above. The cost from each scenario is calculated from a vessel owner and the chain point of view. Firstly, the results of the maritime cost for the Asia – Europe route are discussed, followed by the results for the container loop from the US to Europe.

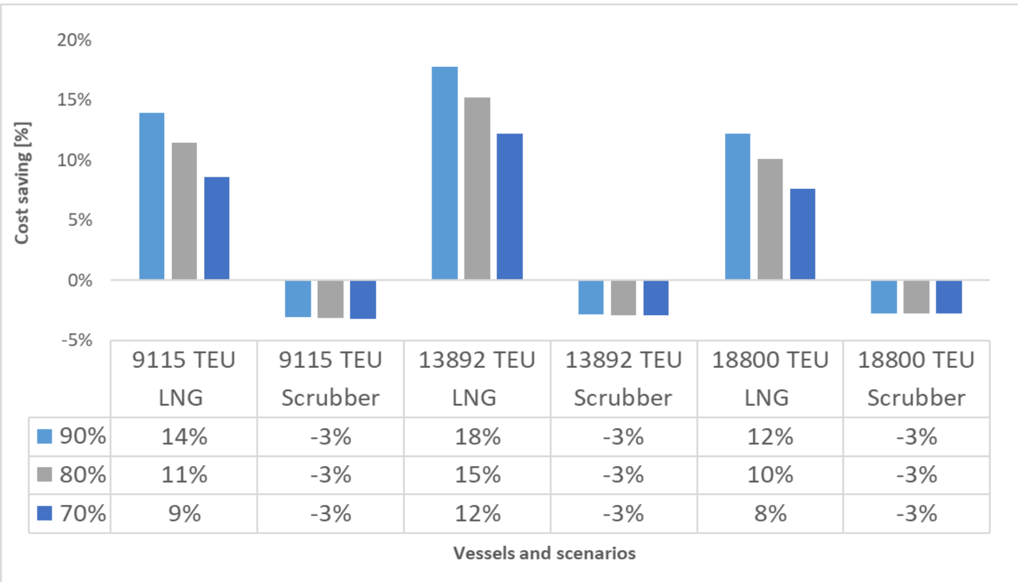
5.5.1. Asia to Europe route

Each researched route is divided into two sub-sections. The results of the vessel owner's costs are given in the first sub-section, while in the second sub-section, the results for the supply chain impact are reported.

5.5.1.1. Vessel owner cost (Asia – EU) with slow-steaming

The cost differential for the two alternative scenarios compared to the reference scenario is given. The different vessel types and the three different speeds are considered for each scenario. Fig. 5.4 presents the results.

Figure 5. 4: Relative changes for the maritime cost (vessel owner's cost) from Asia to EU for different ship types



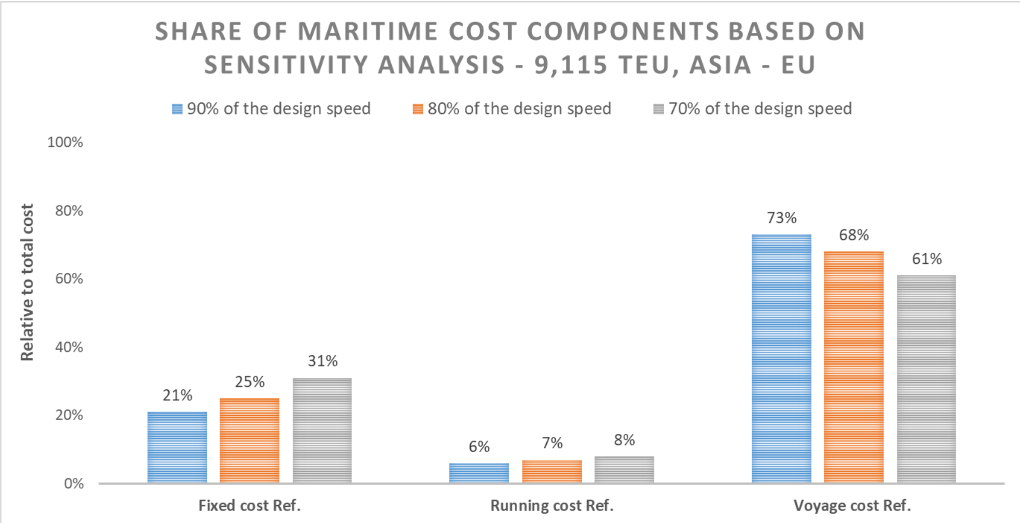
The results show that the most economical alternative technology would be the LNG system for the Asia- EU loop since it features the highest cost savings compared to other scenarios. However, for vessels of 18,800 TEU, the maritime cost increases significantly, which reduces cost savings compared to the two different vessel sizes.

As the size of the vessel increases, the maritime cost enhances correspondingly; however, since, for the vessel of 18,800 TEU, the design speed and the installed power of the propulsion parameter are lower than the vessel of 13,892 TEU, therefore, the maritime cost for this vessel is lower (because fuel consumption is derived from installed power and if it is lower, it does affect the maritime cost).

Besides, the maritime cost decreases by applying speed reduction for all three scenarios. The reason is that speed reduction leads to a decline in fuel consumption, consequently reducing total maritime costs.

Under slow steaming sensitivity analysis, the share of maritime cost components such as fixed, running, and voyage costs have fluctuated in different design speeds, respectively. The results of this alteration in the reference scenario and 9,115 TEU are plotted in Figure 5.5.

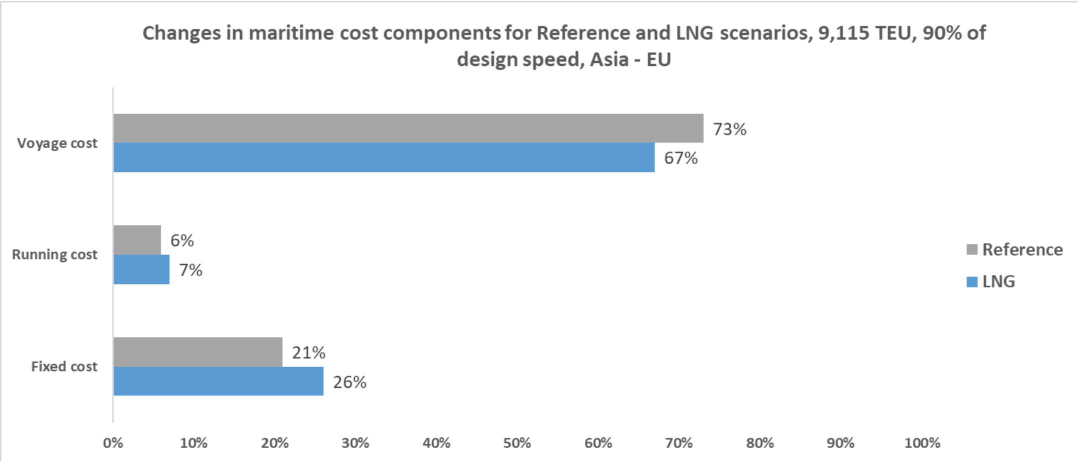
Figure 5. 5: Share of maritime cost components based on sensitivity analysis – 9,115 TEU – Asia – EU – Reference scenario



Firstly, it should be noted that most of the maritime costs pertain to voyage costs. Secondly, the change in fixed cost is greater than in running cost, and in both cases, the costs have risen by reducing the vessel speed. It can be justified that under slow steaming, the vessel needs more time to complete the trip, and as a result, there is an expansion in the ship-related costs.

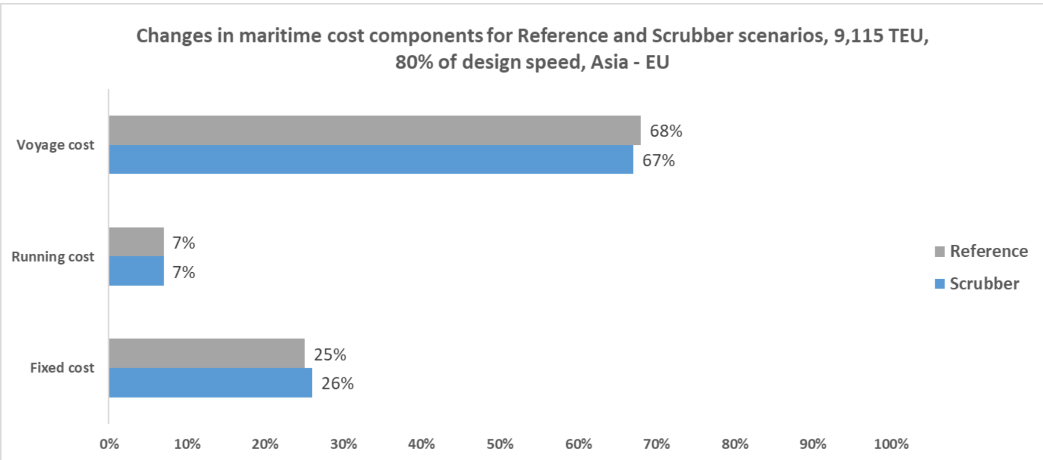
On the other hand, as the design speed of the ship decreases, the voyage cost declines as well. It can be interpreted that applying slow steaming can lead to a fuel consumption reduction. In addition, taking 90% design speed as an example and by comparing the reference scenario with the LNG scenario, it is observed that the fixed and running costs have gone up slightly in the LNG scenario, whereas, due to lower LNG price, the voyage cost in LNG scenario has dwindled modestly.

Figure 5. 6: Changes in maritime cost components for reference and LNG scenarios – 9,115 TEU – 90% of design speed – Asia - EU



As another example, the reference and scrubber scenarios in 80% of design speed have been compared, and the same findings are obtained. However, the alteration is insignificant in this case, and both scenarios display almost the same results.

Figure 5. 7: Changes in maritime cost components for reference and Scrubber scenarios – 9,115 TEU – 80% of design speed – Asia - EU

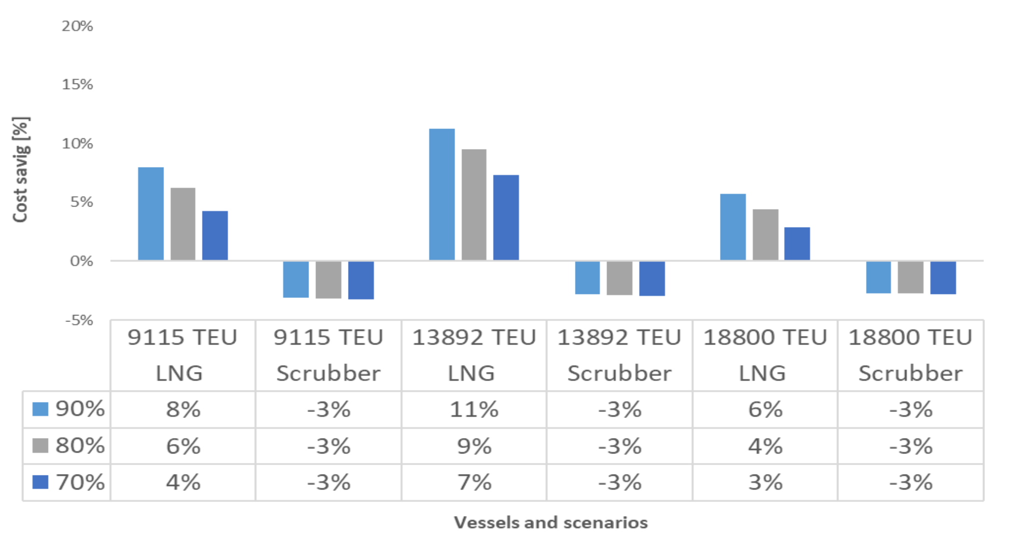


The same comparison accomplishes the trade route from the US to the EU; Figures B.5.6 until B.5.8 in Appendix B plot the results. Interestingly, the same observations are obtained.

5.5.1.2. Vessel owner cost (Asia – EU) with fluctuating the fuel price

Furthermore, for the same scenarios and variations of speeds, the calculations are repeated by changing the fuel price of MDO and LNG. Figure 5.8 depicts the cost savings of alternative solutions concerning the reference scenario.

Figure 5. 8: Relative changes for the maritime cost (vessel owner's cost) from Asia to EU for different ship types with three vessel's speeds 90%, 80%, 70% (by increasing the price of LNG and decreasing the price of MDO)



	9115 TEU LNG	9115 TEU Scrubber	13892 TEU LNG	13892 TEU Scrubber	18800 TEU LNG	18800 TEU Scrubber
90%	8%	-3%	11%	-3%	6%	-3%
80%	6%	-3%	9%	-3%	4%	-3%
70%	4%	-3%	7%	-3%	3%	-3%

By comparing Figs. 5.4 and 5.8, some new results are achieved. On the Asia – Europe route, comparing three scenarios shows that for both the reference and scrubber scenarios, the maritime cost decreases gradually concerning the base fuel price situation (cost savings remain almost the same), while in the LNG scenario, this cost increases, which shows the decrease in cost savings.

Similar to the base fuel price situation, the LNG system remains the cheapest, and the cost-saving of this system is higher than under the scrubber scenario. It points out that the fuel price does affect the maritime cost significantly, and by increasing the fuel price of LNG, the cost savings is reduced compared to the base fuel price situation.

Internalization of external cost

By internalizing the external cost of pollutants into the calculation (see Table 5. 21), it is derived that in the Asia - EU route and taking 13,892 TEU as an example, the total maritime cost will increase by on average 12% compared to not considering the external cost. Moreover, to figure out the impact of the updated external cost of pollutants, it is assumed that the external costs of pollutants such as SO_x, NO_x, CO_2, and PM are doubled in the calculation process. Table 5.22 plots the results.

Table 5. 21: The update of external costs of pollutants

Type of cost	The initial value (EUR/ton)	The doubled value (EUR/ton)
Cost SO_x	0.04	0.08
Cost NO_x	1328	2656
Cost PM10	0.48	0.96
Cost CO_2	25	50

Table 5. 22: Comparison of total maritime cost based on external costs of pollutants

Alternatives	The change in total maritime cost (comparison of initial values (Table 5.17) with No external cost)	The change in total maritime cost (comparison of doubled values (Table 5. 21) with No external cost)	The change in total maritime cost (comparison of doubled values with initial values)
MDO	11.63%	23.25%	10%
LNG	12.33%	24.65%	11%
Scrubbers	11.63%	23.25%	10%

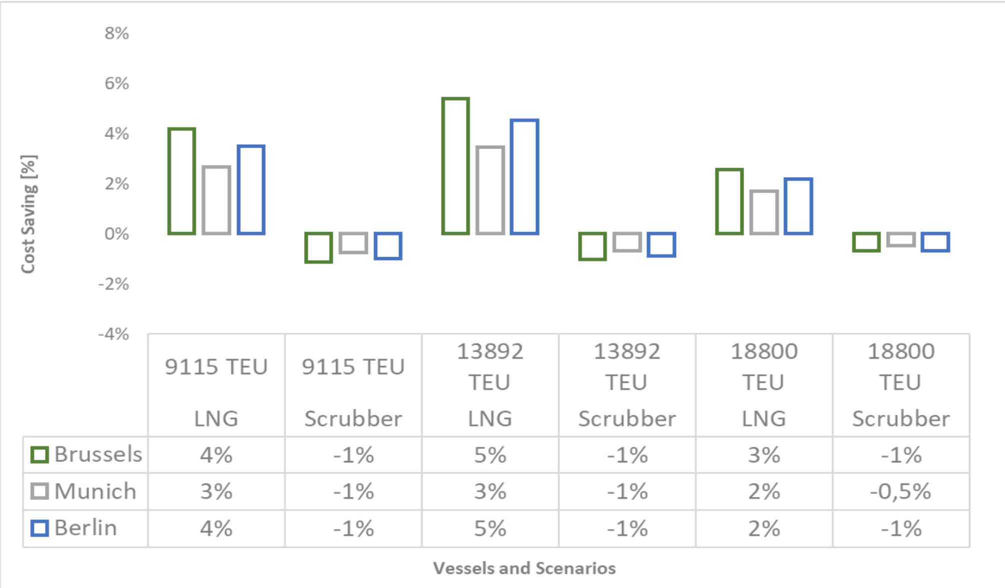
The results demonstrate that the total maritime cost depends on the external cost internalization application. The obtained results reveal that the total maritime cost will increase by doubling the external cost of pollutants by roughly 10% compared to the initial values for each alternative option.

If the price elasticity of demand for maritime transport is known, it is possible to estimate the reduction in the maritime transport volume if the external cost is internalized. However, this issue is out of the scope of the objectives of this Ph.D. and can be considered a subject for further research.

5.5.1.3. Supply chain cost impact (Asia – EU) with slow-steaming

The generalized chain cost for each mentioned destination in Table 5.13 is reported in Fig. 5.9. In this Figure, only the results for 90% of the design speed of the vessel size are plotted.

Figure 5. 9: Relative changes for supply chain cost from Shanghai to EU for different ship types



	9115 TEU LNG	9115 TEU Scrubber	13892 TEU LNG	13892 TEU Scrubber	18800 TEU LNG	18800 TEU Scrubber
Brussels	4%	-1%	5%	-1%	3%	-1%
Munich	3%	-1%	3%	-1%	2%	-0,5%
Berlin	4%	-1%	5%	-1%	2%	-1%

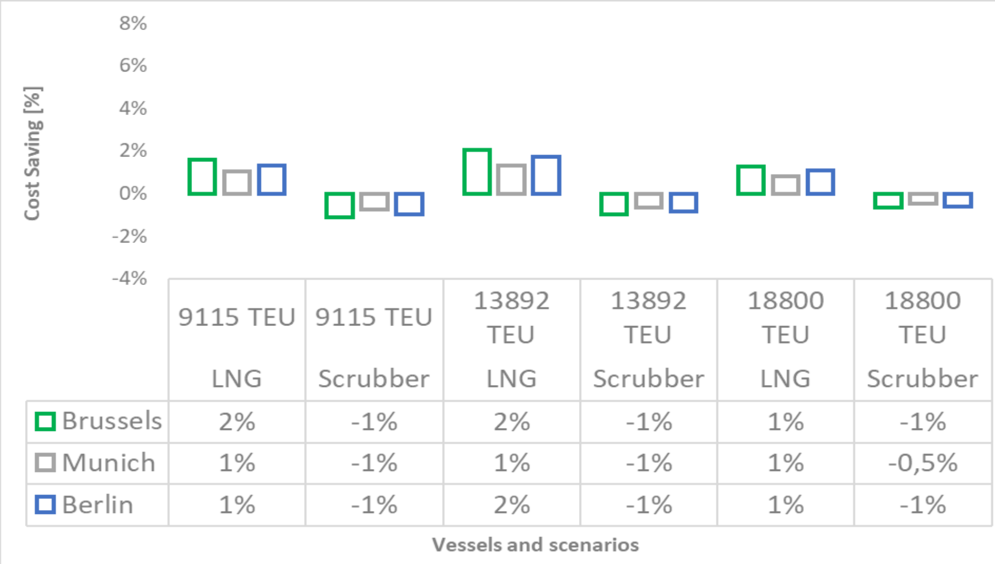
By comparing the generalized chain cost obtained for each destination, it is observed that the cost-saving depends on the distance to the port. On the route from Shanghai to Brussels (the lowest generalized chain cost is obtained via the port of Zeebrugge), most of the cost is made up of maritime cost because the hinterland cost is relatively low, which states that the largest cost-saving is for Brussels compared to the other cities. However, by transporting the cargo from Shanghai to Munich (the lowest generalized chain cost is obtained via the port of Bremerhaven) or Berlin (the lowest generalized chain cost is obtained via the port of Hamburg), the hinterland distances are longer; and consequently, the hinterland cost in larger.

Moreover, comparing the cost savings of the LNG scenario at 90% of the speed (5.3 and 5.8) shows that the effect of using alternative fuel technology is higher for the vessel owner than for the cargo owner. For example, the cost savings for the vessel owner deploying a ship of 9115 TEU equals 14%, while this impact from a chain cost perspective reduces to 4%. In the case of a 13,892 TEU ship, the cost savings dropped from 18% to approximately 5%. In other words, the impacts are relatively high for cost savings from the vessel owner's point of view for LNG propulsion, but from a supply chain perspective, this effect is lower.

5.5.1.4. Supply chain cost impact (Asia – EU) with fluctuating the fuel price

New results are obtained and plotted by changing LNG and MDO prices in Figure 5.10.

Figure 5. 10: Relative changes for supply chain cost from Shanghai to EU for different ship types (by increasing the price of LNG and decreasing the price of MDO)



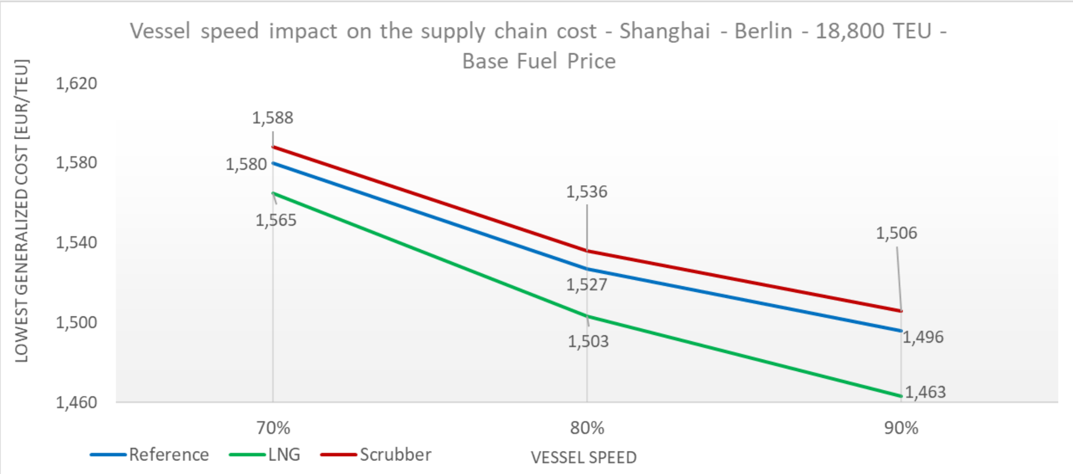
	9115 TEU LNG	9115 TEU Scrubber	13892 TEU LNG	13892 TEU Scrubber	18800 TEU LNG	18800 TEU Scrubber
Brussels	2%	-1%	2%	-1%	1%	-1%
Munich	1%	-1%	1%	-1%	1%	-0,5%
Berlin	1%	-1%	2%	-1%	1%	-1%

By comparing Figs. 5.9 and 5.10, it can be observed that the fuel price also affects the generalized cost. Since the LNG cost increases, the generalized cost grows as well, and it leads to the reduction of cost savings of LNG compared to the base fuel price situation. However, the cost savings remain approximately unchanged for the scrubber technology compared to the base fuel price (a slight change in cost-saving). The LNG propulsion leads to higher cost savings for the base and alternative fuel prices and reflects a better economic option than scrubber technology. This ratio is not significant and is about 5% at the maximum level for ship type 13,892 TEU.

5.5.1.5. Supply chain cost impact (Asia – EU) with slow-steaming and fuel price sensitivity analysis

Taking 18,800 TEU as an example for the maritime route between Shanghai and Berlin, the influence of speed reduction on the generalized chain cost for both base and alteration fuel prices is plotted in the following figures.

Figure 5. 11: Generalized chain cost and slow-steaming in base fuel price

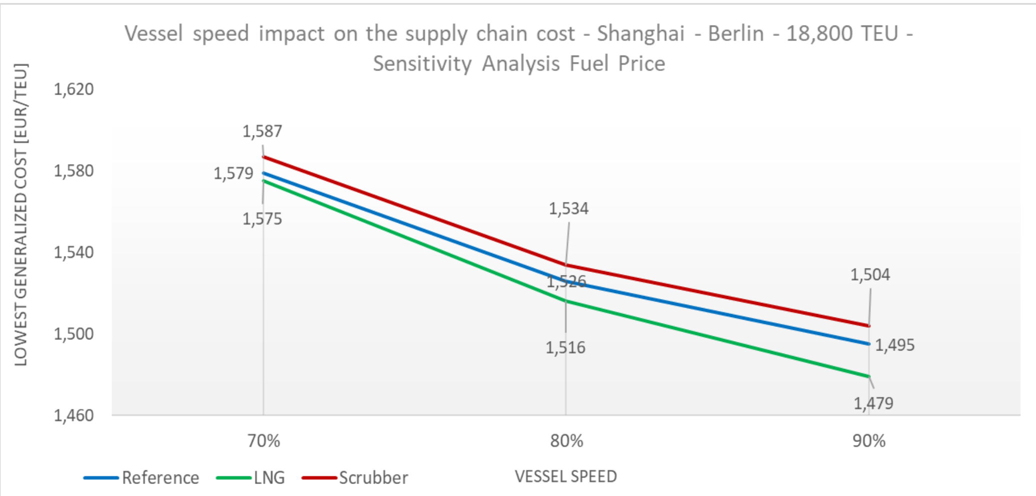


As mentioned, the LNG scenario presents the lowest generalized cost for all speed reductions compared to the reference and scrubber scenarios.

However, this cost rises for all three scenarios by reducing the vessel speed. The reason is that lowering the speed vessel leads to a longer transit time, and it causes an increment in the supply chain cost. This increase is more significant for high-value cargo.

On the other hand, by decreasing the fuel price of MDO and increasing the fuel price of LNG, it is observed that the supply chain cost for all speed alterations in the LNG scenario increases gradually compared to base fuel price, while, scrubber scenario displays the same results.

Figure 5. 12: Generalized chain cost and slow-steaming in fuel price sensitivity analysis



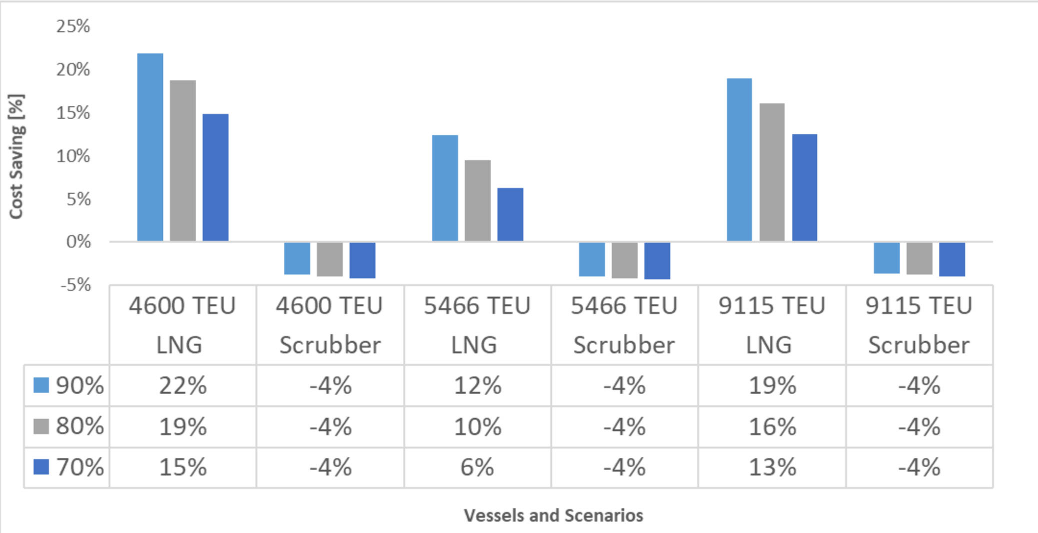
5.5.2. US to Europe route

In parallel, the vessel owner cost and the generalized chain cost are calculated for the trade lane US-Europe.

5.5.2.1. Vessel owner cost (US – EU) with slow-steaming

The cost savings of different technologies are reported in Fig. 5.13.

Figure 5. 13: Relative changes for the maritime cost (vessel owner's cost) from the US to EU for different ship types



	4600 TEU LNG	4600 TEU Scrubber	5466 TEU LNG	5466 TEU Scrubber	9115 TEU LNG	9115 TEU Scrubber
90%	22%	-4%	12%	-4%	19%	-4%
80%	19%	-4%	10%	-4%	16%	-4%
70%	15%	-4%	6%	-4%	13%	-4%

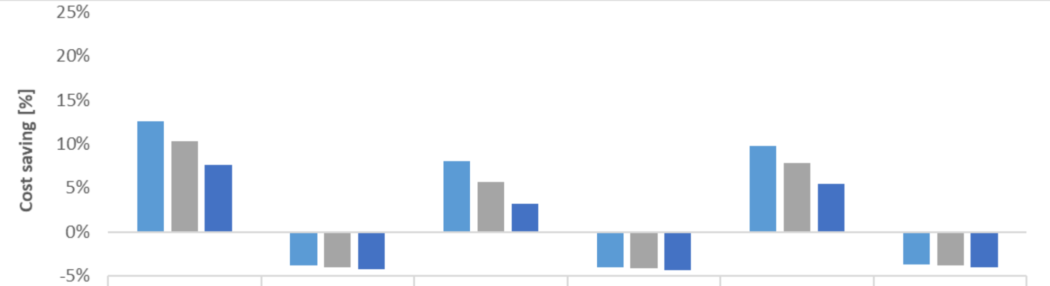
According to the above Table, for all the vessels, there are positive cost savings of LNG propulsion, which states the lowest maritime cost compared to the other options. Besides, the scrubber system is the most expensive option; however, this value is not significant by representing only a 4% cost increment compared to the reference scenario.

By increasing the size of the vessel, the maritime cost raises as well; however, since, for the vessel of 5,466 TEU, the installed power of the propulsion parameter and design speed is smaller than for a vessel of 4,600 TEU, therefore, the maritime cost for this vessel is lower than for the other two (because fuel consumption is derived from installed power and if it is lower, it does affect the maritime cost).

5.5.2.2. Vessel owner cost (US – EU) with fluctuating the fuel price

Fig. 5.14 depicts the sensitivity analysis results by changing the fuel prices of LNG and MDO.

Figure 5. 14: Relative changes for the maritime cost (vessel owner's cost) from the US to the EU for different ship types (by increasing the price of LNG and decreasing the price of MDO)



	4600 TEU LNG	4600 TEU Scrubber	5466 TEU LNG	5466 TEU Scrubber	9115 TEU LNG	9115 TEU Scrubber
90%	13%	-4%	8%	-4%	10%	-4%
80%	10%	-4%	6%	-4%	8%	-4%
70%	8%	-4%	3%	-4%	5%	-4%

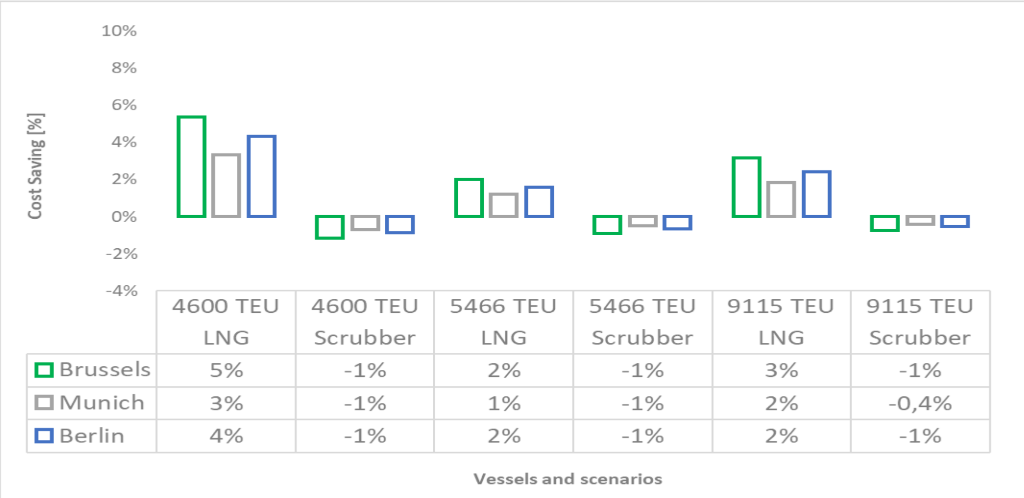
On this route, by comparing Figs. 5.13 and 5.14, the findings for the US – Europe route are as follows: the maritime cost reduces gradually for both the reference and scrubber scenarios. However, for the LNG system, the maritime cost increases for all the vessel sizes, which leads to the reduction of the cost savings of the LNG system concerning the base fuel price situation.

For example, for the ship type of 4,600 TEU and 90% speed, the cost savings diminish from 22% to 13% by changing the LNG price. This fact is valid for ship types 5,466 TEU and 9,115 TEU by decreasing the cost-saving from 12% to 8% and 19% to 10%, respectively. Therefore, it can be concluded that, by changing the fuel price, LNG becomes a less economical option but still has the highest cost savings compared to the scrubber system in the US – EU route.

5.5.2.3. Supply chain cost impact (US – EU) with slow-steaming

Regarding the generalized chain cost, the results of the analysis are presented in Fig. 5.15

Figure 5. 15: Relative changes for supply chain cost from Jacksonville to EU for different ship types



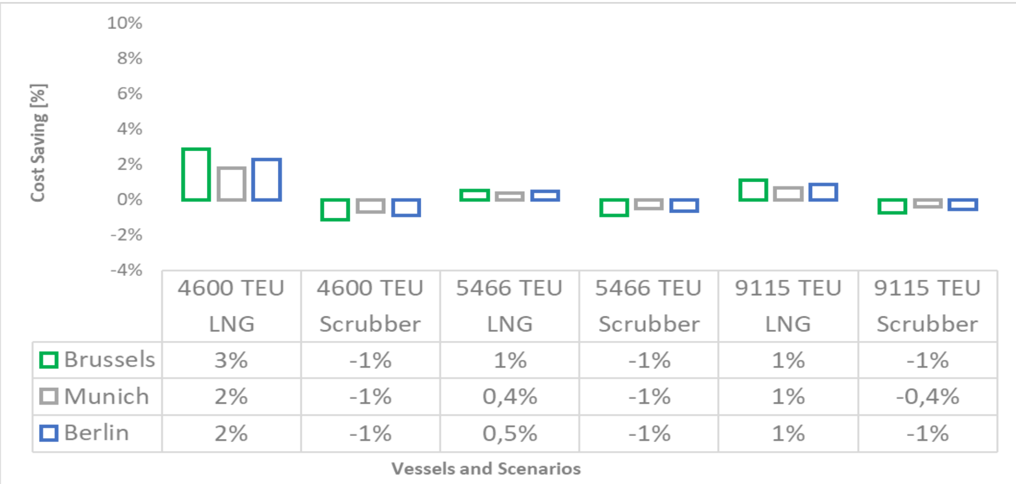
	4600 TEU LNG	4600 TEU Scrubber	5466 TEU LNG	5466 TEU Scrubber	9115 TEU LNG	9115 TEU Scrubber
Brussels	5%	-1%	2%	-1%	3%	-1%
Munich	3%	-1%	1%	-1%	2%	-0,4%
Berlin	4%	-1%	2%	-1%	2%	-1%

On the route from Jacksonville to Europe, the lowest generalized cost is obtained via the port of Antwerp for the final destination Brussels, while for the trip from Jacksonville to Munich or Berlin, the lowest generalized cost is incurred via the port of Bremerhaven.

5.5.2.4. Supply chain cost impact (US – EU) with fluctuating the fuel price

Figure 5.16 gives the results of the supply chain cost for the sensitivity analysis.

Figure 5. 16: Relative changes for supply chain cost from Jacksonville to EU for different ship types (by increasing the price of LNG and decreasing the price of MDO)



	4600 TEU LNG	4600 TEU Scrubber	5466 TEU LNG	5466 TEU Scrubber	9115 TEU LNG	9115 TEU Scrubber
Brussels	3%	-1%	1%	-1%	1%	-1%
Munich	2%	-1%	0,4%	-1%	1%	-0,4%
Berlin	2%	-1%	0,5%	-1%	1%	-1%

By comparing Fig. 5.15 and 5.16, the effect of the fuel price on the supply chain cost is displayed. By increasing the fuel price of LNG, the cost savings of this alternative option decrease compared to the base fuel cost situation. However, the cost savings of the scrubber system remain unchanged; furthermore, by increasing the fuel price of LNG, although the cost savings of this option decrease, it is still a better economic option by presenting the lowest generalized cost.

5.6. Conclusion

International maritime shipping has been confronted and will face new regulations by different policy actors (i.e., IMO, the EU) to reduce the volume of pollutants emitted from vessels globally and in ECA zones more strictly. In this research, two main research questions were investigated; (i) *what are the best alternative options to comply with the ECA regulation according to the literature?* And (ii) o*f those selected technologies, what are the maritime costs from a vessel owner's point of view, and what is the impact of the technologies on the generalized chain cost*?

According to the literature review accomplished in this research, LNG is seen as an alternative solution for maritime shipping. LNG is considered one of the promising solutions that shows better economic evaluation and has a lower emission level. However, the rising concerns about LNG's ability to reduce GHG emissions as an alternative to existing fuels should not be neglected. The second-best option is scrubber technology. The findings of this study confirm that LNG can be considered an alternative and possible solution to replace HFO in maritime shipping as it shows the lowest maritime cost compared to the other alternative technologies (also for different HFO - LNG spreads).

The economic comparison is made with three different scenarios of engine types and the fuel used inside and outside the ECA zones. Moreover, this comparison has been put forward by using two different levels of fuel prices by increasing the fuel price of LNG by 70 [EUR/ton] and decreasing the price of MDO by 80 [EUR/ton] to realize the effect of fuel price on the maritime and chain costs. The external costs of pollutants including SO_x, NO_x, CO_2, and PM are factored into this model.

Based on the performed analysis, firstly, it is found that the LNG system has the lowest maritime cost compared to the reference and scrubber scenarios for both Asia and the US to EU routes. Secondly, the cost savings of the LNG scenario are higher than for the scrubber scenario concerning the reference scenario, while the cost savings of the scrubber scenario are negative for all the vessels for both vessel owner maritime cost and supply chain cost. Therefore, the results conclude that LNG propulsion is the most economical option for both Asia-EU and US-EU routes by demonstrating the lowest vessel owner cost and generalized chain cost compared to the scrubber technology and reference scenario.

In addition, by comparing the total maritime cost of the vessels for all three scenarios and both routes, it is observed that maritime transport cost reduces as the percentage of design speed decreases. Besides, the maritime cost rises as the size of the vessel increases.

Interestingly, by analyzing the obtained results, it can be derived that the supply chain impact depends not only on ship size but also on maritime distance. It interprets that, in a longer maritime distance from Asia to Europe, the maritime cost is relatively higher than the shorter nautical distance from the US to Europe, and in this case, the majority of expenses relate to hinterland costs.

By performing sensitivity analysis and increasing the LNG price, and decreasing the MDO price, it is observed that the LNG system remains the most economical alternative solution. However, the cost savings reduce significantly compared to base fuel price. The reason is that the maritime cost of LNG increases considerably by increasing the fuel price of LNG, and at the same time, the total maritime cost of the reference scenario decreases by diminishing the fuel price of MDO, which leads to the reduction of the cost savings of LNG propulsion. Moreover, the cost savings of the scrubber scenario concerning the reference scenario do change slowly.

This study has the capability of applying to other maritime routes. First of all, the CCM needs to be updated. The existing ports in the loop should be gathered and added to the model along with all the necessary data regarding the maximum allowable draft port, terminal's infrastructure and equipment, rate of cargo loading and unloading in the terminal, traffic data, and all the port and terminal related costs such as port dues, container handling cost, terminal operation cost, etc. [27].

Besides, different containerized vessels can be added to the model. In this case, the information regarding the vessels needs to be adjusted to the model;

(i) Operation data, port approach speed, design speed, average payload ship, etc.
(ii) Technical data such as dimensions (length overall, beam, depth), propulsion parameters (installed power, fuel consumption of the engines), displacement cargo, deadweight, etc.
(iii) Cost data such as running cost, voyage cost, and capital cost[28] such as the purchase cost of the ship, fuel cost, repair and maintenance costs, fuel cost, etc.

Finally, based on the above parameters and obtained data, the desirable maritime route is defined, and the total maritime cost and the generalized cost are calculated.

[27] Read chapter 3 for extra information.
[28] Read chapter 3 for extra information.

Chapter 6: The feasibility and potential of enhancing the supervision of maritime container supply chain from an economic perspective

6.1. Introduction

The increase in international trade, primarily through container transport, has been accompanied by the emergence of various types of smuggling, including narcotics, weapons, cigarettes, explosives, and radioactive and nuclear substances, along with the potential risks and threats associated with these activities. One of the most remarkable types of smuggling is the illicit trafficking of narcotics – primarily cocaine – through container transport. In 2016, about 70 tonnes of cocaine were seized in European ports (European Monitoring Centre for Drugs and Drug Addiction, 2018). It is vital to note that the current inspection policy, means of inspection, and procedures are insufficient to counter this problem efficiently.

Ensuring the safety and security of maritime shipping and minimizing the risks and the potential losses is an issue of great importance (Chang et al. 2014). Security must be followed by in-process control to monitor shipments in the transition phase (Thai, 2009).

The volume of freight loaded or unloaded in Antwerp has doubled over the past 20 years to 235 million tonnes, and in 2018 [29], the port of Antwerp handled 11,100,408 TEU (Annual report 2019), which shows 28% growth compared to 2008 and a 6% increase compared to 2017. However, the intertwisted of international drug trafficking and organized crime, which has settled in the city and its environs, has been a significant source of concern for security actors and policymakers in Antwerp for several years now (Easton 2020; Sys and Vanelslander 2020). In 2020, Easton investigated the flows of drugs in the port of Antwerp and explained the so-called Stroomplan to tackle the import and transit of cocaine in the port of Antwerp.

This chapter sheds some light on the increase in the security of the supply chain by enhancing the supervision of import cargo which aims at reducing illicit trafficking and leads to improvement and enhancement of the economic and social aspects of the MarSC. Thus, this chapter assesses the feasibility of enhancing the supervision of the maritime container supply chain from an economic perspective for the port of Antwerp. More importantly, it develops an innovative scanning evaluation cost model based on various scanning rates and locations applied worldwide.

Therefore, for the objectives of this research, three different technologies being Imaging, electromechanical techniques, and Artificial Intelligence (AI), are applied as the leading technologies for supporting the efforts of Customs Authorities to enhance the non-intrusive supervision containers[30].

In this research, the cost and benefit of scanning containerized cargo at the terminal and port levels are assessed, and its possibility without hampering the logistics chain is evaluated.

[29] In the calculation, the reference year is 2018 and container volume is obtained based on this year.
[30] Read section 6.2.3 for extra information.

This chapter addresses the following research questions:

What is the total cost of scanning the containers for the actors involved under various scanning percentages/rates at the terminal level?

- *How will the generalized chain cost change under the increasing scanning rate for the defined maritime routes from several ports in different continents to the port of Antwerp?*

The Port of Antwerp has considered the case study in this research in which the focus is only on container terminals. This research applies a two-part methodology, initiating with multiple interviews to integrate information learned from the technology evaluation with professional expertise., First, a unique scanning cost approach is established to assess the costs incurred by all parties in the scanning scenario in which, in each determined scenario, this analysis determines the overall costs from multiple components.

The supply chain cost evaluation is the second phase of the method, and it evaluates the generalized chain cost under various scanning options for some origin ports in Asia, the Middle East, and South America to Europe.

This chapter pertains to UN SDG 16 *"to reduce illicit financial and arms flows, strengthen the recovery and return of stolen assets, and combat all forms of organized crime."* Besides, the economic and social aspects of sustainability of MarSC are addressed in this research.

This chapter is based on the published paper by Mohseni et al. 2020; however, it is updated with new data and calculations and more detailed results along with more elaboration on the literature review and applied methodology.

The remaining parts of this chapter are organized as follows. Section 6.2 discusses the literature review relevant to maritime safety and security, and section 6.3 argues the interview outcomes and the scenario development. Section 6.4 explains the applied methodologies, namely (i) a novel developed cost calculation model and (ii) the adjustments of the CCM. Section 6.5 reports the detailed results of the calculations, while section 6.6 depicts the generalization of the cost model. Finally, section 6.7 provides the conclusion.

6.2. Literature Review

In this section, a comprehensive review of the safety and security of MarSC is provided, along with the concept of resilience in the MarSC. Afterward, a brief explanation of the available machinery, hardware, and software applied to increase safety and security is presented.

6.2.1. Maritime safety and security

Yang et al. (2013) developed a six-step maritime security assessment methodology supporting risk modeling and decision-making methods. Based on this methodology, the overall security level needs to be monitored and used as a benchmark to measure the security changes of a maritime transport system in its dynamic operational environment.

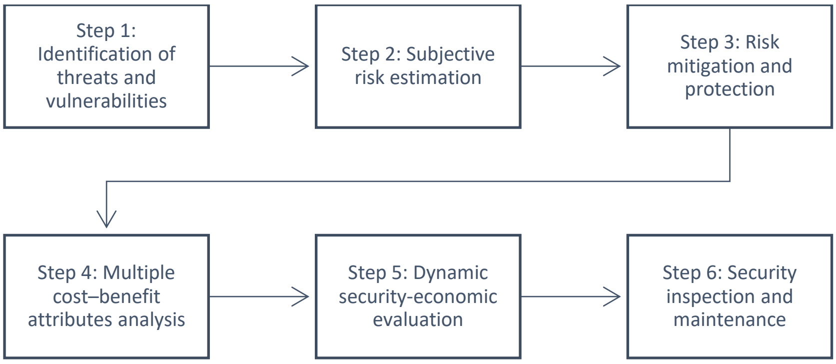
A MarSC is exposed to various natural and man-made risks (Lam & Bai, 2016; C. Wan et al. 2019). Technical failures or human factors cause maritime safety accidents, whereas maritime security incidents typically originate from piratical or terrorist attacks, which both types lead to property damage, financial loss, personal injury, and loss of life (Chang et al. 2014).

The maritime industry's significant safety challenges are considered ship sizes and operational environments; cruise ships and fire; training and crewing level; inadequate risk assessment and poor regulation implementation; piracy and maritime security (AGCS 2012; Z.L. Yang et al. 2013). The complexity of interaction between ports, maritime operations, and supply chains creates vulnerabilities (Barnes & Oloruntoba, 2005). Uncertainty is another essential characteristic in liner shipping, caused by congestion, uncertain handling time, and weather conditions, and will impact the vessel’s reliability, fuel consumption, and emissions (Qi & Song, 2012).

There are three main research challenges on maritime and supply chain vulnerabilities such as (i) less attention on maritime sector in terms of complex networks and resilience and vulnerability; (ii) different concepts of the term vulnerability used in this field and (iii) lack of analysis of vulnerability in a combined way by social network analysis (SNA) and robustness analysis approach (Liu et al. 2018).

Formal safety assessment (FSA) is the premier method currently being used to analyze maritime safety and the formulation of related regulatory policies by the IMO (Psaraftis & Kontovas, 2010; Yang et al., 2013). Based on FSA, Yang et al. (2013) developed a six-step maritime security assessment methodology supporting risk modeling and decision-making methods.

Figure 6. 1: A six-step maritime security assessment methodology



Source: Authors' composition based on Yang et al. 2013

Li et al. (2018) discuss the disruption in land-side and sea-side operations at a container terminal, including extremely bad weather, industrial accidents, natural disasters, traffic accidents, or terrorist attacks.

Safety screening and security checks (a double-check) on the contents of cargo being shipped can influence MarSC implementation (Jasmi & Fernando, 2018). In the maritime industry, communication skills, teamwork skills, leadership, and the employment of highly qualified human resources play a crucial role in ensuring and enhancing safety on board ships (Cicek et al. 2019). The continuous improvements of security can be used as a primary basis to forecast business success in MarSC management (Yang & Wei, 2013).

Visibility has been considered as a new risk parameter in the supply chain in which good visibility will benefit operational efficiency, productivity, and effective planning in the supply chain (Petersen et al. 2005; Yu and Goh, 2014; Wan et al. 2019). Barnes and Oloruntoba 2005 highlight the need for enhanced port crisis management capabilities and suggest a new classification scheme for mapping vulnerability within ports and across supply networks. UNCTAD (2006) argues the potential risk types throughout the MarSC and classifies them into three major fields such as external, internal, and supply chain risks. Table 6.1 describes the effects of maritime risk throughout the supply chain.

Table 6. 1: Risk types of MarSC

Potential risk types	Potential risks	Description
External risks	Natural disaster	Environment risks, such as adverse weather, fire and ice conditions in winter
	Piracy/terrorism	Piracy/terrorism
Supply chain risks	Congestion in port	Capacity problems in the port area
	Ports state control	Port State inspections, vessel detention risk
	Technical downtime	Downtime resulting from periodical dry-docking and technical maintenance
	Operational risk	Ship collision or sinking, the condition of cargo handling equipment, and problems with document interpretation
Internal risk	Human resource management	Lack of skilled workers, carelessness, and a lack of motivation among the workforce
	IT system	Cyber-attack, IT system breakdown

Source: Authors' composition based on UNCTAD 2006

Internal risks are deemed the most important among all risk factors compared to external risks and supply chain risks. Also, internal risks have the most impact on the customer service level. The top three risks are IT systems, operational risks, and human resource management risks (Lam & Bai, 2016). Similarly, Chang et al. (2014) state that shipping managers should pay more attention to the risks associated with information flow and physical flow to reduce safety and security damage. The top three risk factors affecting container shipping's safety and security are (i) attacks from terrorists, (ii) damage to ship or quay due to improper berth operations, and (iii) transportation of dangerous goods.

Table 6. 2: Risk categories and risk factors of MarSC

Risk category	Relevant risk factors
Information flow	Hiding cargo information by shippers; Extra service information requested by shippers; Information delay by using different communication channels; Lack of information security; IT infrastructure breakdown
Physical flow	Damage caused by transporting dangerous goods; Terrorist attacks; Damage to ship or quay due to improper berth operations; Cargos detained by customs; Oil price increase; Unstable weather; Port congestion; Container shortage
Payment flow	Shippers' bankruptcy; Financial crisis in the loan countries; Abandoning cargos in the port of destination by shippers; Currency exchange in the payment process; Payment delay from partners or shippers; Breaking contract and reducing container volume by shippers

Source: Authors' composition based on C. H. Chang et al. 2014

Balmat et al. (2011) evaluate the maritime risk assessment within the framework of the environment protection and pollution prevention based on the developed decision-making system, which allows defining the risk factors based on static parameters (ship's characteristics), meteorological conditions (weather conditions), and dynamic parameters (ship's speed). Wan et al. (2019) develop a model that identifies the risk events relating to MarSCs from a whole supply chain perspective involving multiple dimensions such as technical, operational, managerial, and financial risks. The main focus is on two risk parameters (i.e., likelihood and consequence).

6.2.2. MarSC resilience

Supply chain resilience is about the ability of the supply chain to return to its original state or a more desirable state after a disturbance and to avoid the occurrence of failure modes (Azevedo et al. 2008); also, it is the ability to tackle unexpected disruptions across the supply chain (Lam & Bai, 2016). According to Sheffi (2006), supply chain resilience empowers companies' proactive response to changing market demand and disruption ahead of their competitors.

As substantial research, Lam & Bai (2016) investigate the application of the QFD approach to prioritize resilience solutions in the shipping industry. A QFD model is employed to translate customer requirements (CR) into shipping companies' design requirements (DR), and it adopts UNCTAD (2006)'s classification method and specifies three risk groups: (i) external risks (environmental risks), (ii) supply-chain risks (network-related) and (iii) internal risks (organization related). The study's findings provide six resilience measures to mitigate MarSC's risks for shipping lines in which the essential measure is the contingency plan. Other plans are monitoring and maintenance, supply chain relationship management, advanced IT systems, strategic alliances, and forecast accuracy. Furthermore, six customer requirements are defined in which the top three are (i) on-time and hassle-free shipment delivery, (ii) easy real-time shipment tracking, and (iii) professional and helpful staff followed by (iv) shipment safety and security, (v) error-free B/L and invoices and (vi) fast service.

6.2.3. State of the art technology

Customs Authorities are a central player in the cross-border movement of goods and people. Many customs authorities are considering using various technologies to contribute to the efficient simplification and enhancement of border control. Technology is changing rapidly, and it will impact the current processes of the Customs Authority. AI, blockchain, electromechanical techniques, the Internet of Things (IoT), and imaging will change how it processes border traffic. This section details the technologies mentioned above and identifies the ones with potential for this study.

Imaging

In the context of this study, imaging is defined as the domain in which electromagnetic radiation is used to penetrate objects (in part or whole) for internal analysis. Any radiation detected is processed into an image, which an operator typically interprets. Customs Authorities worldwide use this most familiar and widely known imaging technique, X-ray imaging, to inspect different types of cargo (e.g., luggage and containers). It can enable customs inspectors to identify what is inside a container, to determine whether it requires additional checking (COSMIC project 2019, Rogers et al. 2017, Kretschmann and Münsterberg 2017, Astolfo et al. 2017, Jaccard et al. 2016, Van Liew 2016, Valkovic et al. 2016, Saverskiy 2015; Kolkoori et al. 2014, Firsching et al. 2013).

Electromechanical techniques

They are regarded as a combination of air sampling and the analysis of that air. A critical advantage of this technique is that it makes it possible to obtain an overview of the components present in the air, thereby helping the Customs Authority identify containers with possible contraband inside. Also, the time needed to conduct analysis is relatively short, often a minute or less (Giannoukos et al. 2016). This technique could detect narcotics inside containers for customs without opening them (Combating Terrorism Technical Support Office 2018).

Blockchain

A highly promising technological domain is defined as a sophisticated, cryptographically distributed ledger architecture with a continuously expanding list of records known as ‘blocks.’ Blockchain is used to move any data securely and quickly and transmit documentation of such changes to the participants in the blockchain network instantly, reliably, and immutably. The application of this technology would allow the end-to-end availability of supply chain information and a single shared source of truth (Popov et al. 2019; Carlan et al. 2017). Blockchain technology has considerable potential to impact customs-related processes (e.g., declaration, exchange of information, identity management).

Internet of Things (IoT)

It is defined as the inter-networking of connected devices and smart devices. Electronics, software, sensors, actuators, and network connectivity are embedded in vehicles, buildings, and other items, enabling them to collect and exchange data. Various initiatives have been launched within the context of transport and customs, including smart ports (e.g., Hamburg), innovative seals, and smart containers (e.g., asset tracking of perishable goods) (Huh et al. 2016; Dong et al. 2013). Like blockchain, IoT requires sector-wide implementation before it can be integrated into customs processes (Vannieuwenborg 2018).

AI

The domain of AI is broad, and it can be applied in multiple circumstances. It refers to developing computer systems capable of performing tasks that typically require human intelligence (e.g., visual perception, speech recognition, decision-making, and translation between languages). AI is already in use within customs, particularly in intelligent logistics regulatory equipment, innovative regulatory system, intelligent cooperation with other government agencies and customs administrations, and intelligent cooperation between customs administrations and companies. It could also be used for analyzing various data sources based on parameters to indicate whether a particular container should be chosen for manual inspection (Akcay et al. 2018, Fombellida 2014).

The literature review reveals that customs are already applying imaging and Electromechanical techniques domains. Technological innovation within those domains or the development of different uses for existing processes within other sectors could help the Customs Authority improve containers' non-intrusive inspection. However, blockchain and IoT are still immature, and they require initiatives supported by an entire industry before integrating into customs processes.

Moreover, AI can have an immense impact on customs processes. Given enough data and training, the technology would conduct human actions more efficiently than humans can. The number of border controls will increase along with the continuing increase in port container transport.

Overview of relevant literature investigates the risk factors, risk mitigation issues, legislation, and procedures concerning maritime safety and security. Prior studies have shown that the establishment of safety and security in MarSC is one of the most significant interests and critical concerns, as maritime shipping is exposed to various threats. Additionally, supervision enhancement of container supply chain supervision is crucial to improving safety and security while reducing the possibility of illicit trafficking. This chapter examines the viability of establishing a new cost calculation model to enhance the supervision of the maritime container supply chain from an economic standpoint for the port of Antwerp. The model considers different stakeholders and cost components based on three scanning rates and key scanning locations.

6.3. Interview and scenario development

Several interviews have been held with scanning technology providers and with associations (and their members) of shipping companies, freight forwarders, shippers, trucking companies, terminal operators, and customs authorities to combine knowledge gained from the technological assessment with experience from the professional field.

The obtained information is beneficial to identify the various process steps happening during the port activities, along with their corresponding locations, timing, and dimensions. Furthermore, the results of the interviews are used as the basis for considering future scanning scenarios.

6.3.1. Interview and data collection

A qualitative study is conducted to generate insight into the diverse container scanning processes at the Port of Antwerp and the possibilities and limitations of the different chain actors concerning changes in these procedures in the case of enhancing scanning rates. The output of interviews about the current scanning process is reported in the following section, which will be the basis for future scenarios and the actual calculations.

The performed interviews with sector associations show that 100% screening is completed and a selection for further investigation (scanning and physical inspection) is made, using (partly automated) risk-analysis tools based on the information provided through various information sources and documents, including the Entry Notification Summary (ENS), the Declaration of Temporary storage, the Commercial Manifest and the Customs Declaration document. Currently, the risk-analysis procedure leads to the scanning of less than 1% of all incoming containers.

Communication process

Once a selection is made for scanning, the decision is communicated automatically to the various parties involved (shipping agent, terminal operator, declarant, monitoring team). If the selected containers do not appear at the designated scanning site on time, the Customs Authority is entitled to take measures, including the imposition of fines.

Scanning process

This study focuses only on the dedicated container terminals where the scanner type is fixed. The current scanning process at the container terminals of the port of Antwerp is accomplished in a specific site outside the terminal.

Once a container is selected for scanning based on the risk analysis, the Customs Authority is responsible for choosing the type of scanner, either a fixed or relocatable one, depending on various considerations (e.g., whether physical is required).

The duration of the scanning process can vary, depending on the location of the scanning site, the type of scanning equipment, and the image analysis. The fixed scanning location needs approximately one hour (for the transition from the container terminal to the scanning location outside the terminal) and five minutes for scanning itself. The image analysis takes 5–30 minutes (in the calculation, it is considered on average fifteen minutes), depending on the quality of the image, the contents of the scanned container, and the experience of the image analyst.

Physical inspection

Physical inspection is performed in the following situations:

- The risk analysis identifies the container as a high potential risk.
- The container's image is inconsistent with the declaration documents or provides insufficient information.
- Some containers are selected for physical inspection in advance, regardless of the scanned process.

The time required for physical verification depends on all of the conditions above, whether the entire container must be unpacked, and the type of goods (e.g., the complexity of the content). The additional costs associated with physical verification are around €700– €1000, and they are to be paid by shippers and billed to the final customer. Based on the interviews, approximately 5%–8% of all physical verifications result in false positives.

The number of required operators depends on the type of scanning device. For the fixed scanning system, 5 – 7 operators for each tunnel are needed, and if both tunnels are used simultaneously, then 8 – 9 operators are required overall. Two analysts are required to analyze the scanning results per each working shift, which means four people per day.

The interviews with sector associations reveal that the stakeholders perceive both problems and positive aspects about the current scanning process and the potential for future alternatives. The advantages and disadvantages of the current scanning process, both from technology and operational perspectives, are plotted in Table 6.3. Based on interviews, it can be noted that the current scanning process and operation are not effective in overcoming illicit trafficking at the port of Antwerp.

Table 6. 3: Positive and negative aspects of the current scanning process

Type of scanning system	Advantages	Disadvantages
Fixed and relocatable X-ray container scanners	Relatively good results for different types of cargo compared to the mobile scanner due to dual-view imaging Shipping companies are informed in advance.	Scanning location outside the terminal leads to (i) additional movements, time, and costs for transportation to scanning location (ii) high risk of escape during transport. There is suboptimal image quality with containers with complicated cargo or organic materials (drugs) detection. Time requirement (30 minutes) for starting up the system. The high number of staff required (5 – 7) per scanner.

6.3.2. Scenario development

In this study, several scenarios are taken into account to estimate the economic effect of applying the state of art technologies and new scanning locations to increase the scanning rates while minimizing the delay and congestion in the supply chain process operation at the terminal. In total, five main scenarios are considered. The first scenario is the "reference scenario" and refers to the current scanning operation, while other scenarios belong to alternative or future scenarios compared to the reference situation. Table 6.4 plots the details of each scenario, including scanning rates and locations and the relevant device employed in each scenario. The following sub-sections discuss each scenario is in detail.

Table 6. 4: Scenario development

Scenario	Scanning location	Technology	Scanning rate	
Scenario 1	Current operation: outside the terminal in a specific scanning location	Existing technology: X-ray system	1%	
Scenario 2	Central scanning location inside the terminal	X-ray system FS6000DV	Scenario 2.1	5%
			Scenario 2.2	50%
			Scenario 2.2	100%
Scenario 3	In the OCR lanes at the gate out	X-ray system FS6000DV	Scenario 3.1	5%
			Scenario 3.2	50%
			Scenario 3.2	100%
Scenario 4	Air analysis on the crane	Headspace sampling and ion trapping	Scenario 4.1	5%
			Scenario 4.1	50%
			Scenario 4.1	100%
Scenario 5	Combination of Air analysis on the crane and OCR lanes at the gate out	Headspace sampling and ion trapping and X-ray system FS6000DV	100% of the containers with air analysis and 10% with the X-ray system	

6.3.2.1. Scenario 1

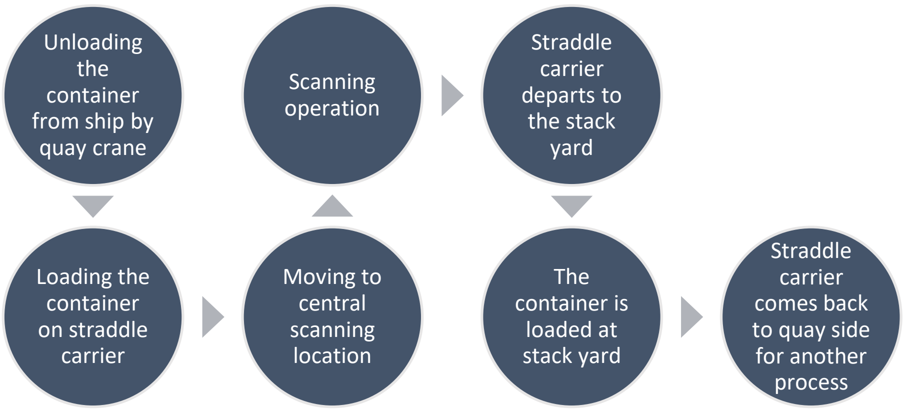
This scenario corresponds to the current implementation of scanning. Currently, only 1% of all imported containers are scanned at the scanning location. The selected containers must depart from the terminal to the scanning location. This study and interviews are assumed to be one hour as a common value for all terminals. After the scanning operation, the container must remain at the scanning location for image analysis results.

Consequently, based on the image analysis, either the container is required to proceed to the physical inspection site for further investigation, or it is allowed to leave the scanning location. In the latter case, most containers (80%) proceed to their final destinations in the hinterland, while only 20% are required to return to the terminal, which generates additional time requirements as these containers must pass through the gate out for a second time. These costs appear as delay time costs in the calculation (DT_c).

6.3.2.2. Scenario 2

In Scenario 2, the scanning operation is performed at the actual terminal itself, and the scanning location is known as the central scanning location inside the terminal. A different scanning system has been used as the FS6000DV X-ray system.
Three different scanning rates are considered in calculating costs: in scenario 2.1, the scanning rate is 5% of all the imported containers, while this value is increased to 50% and 100% in scenarios 2.2 and 2.3, respectively. This scenario makes a difference in the unloading and stacking of the containers inside the terminal. Figure 6.2 displays the unloading and scanning operation in scenario 2.

Figure 6. 2: Scanning operation in scenario 2



After scanning, the container is transported from the scanning location to the stackyard to load the container there. Only 5% of all scanned containers are selected for physical inspection. Furthermore, while the scanned containers are transported to the stack yard, the scanning image is being analyzed to avoid delays in operational processes. If a container requires physical verification, it will be transported from the stack yard to the physical inspection location.

6.3.2.3. Scenario 3

This scenario uses the FS6000DV X-ray technology as the same as scenario 2. In this case, however, the scanning is performed in the OCR lanes at the gate out.
In this scenario, after the scanning operation at OCR lanes, the container must stay there and wait for the image analysis result. Providing enough space for stacking the containers after scanning is an important issue, in which the increase in the scanning rate leads to the rise of the space required. In scenario 3.1, the scanning rate is 5% of all the imported containers, while this value is increased to 50% in scenario 3.2 and 100% in scenario 3.3, respectively.

There are several OCR lanes in each terminal; however, not all the lanes are equipped with scanners. In each scenario and based on the scanning rate, some of the lanes will be equipped with scanners which means as the scanning percentage rises, more scanners are required.

6.3.2.4. Scenario 4

In this scenario, the air analysis is performed on the crane. The technology used is the Electromechanical technique combined with headspace sampling and ion trapping. With this technology, air sampling air analyses are carried out while containers are unloaded from the ship to the quay yard, which takes approximately two minutes [31] . In this scenario, no scanning operations or image analyses are performed. Consequently, physical inspection is required in the case of negative results for containers. In scenario 4.1, the scanning rate is 5% of all the imported containers, while this value is increased to 50% and 100% in scenarios 4.2 and 4.3, respectively.

6.3.2.5. Scenario 5

In this scenario, a combination of two different technologies is considered. First, the electromechanical technique is used for 100% of all the imported containers. Then, 10% of these analyzed containers will be scanned with the FS6000DV X-ray system. The aim is to figure out the efficacy of combining two technologies. The scanning location is considered in the OCR lanes at the gate out (see scenario 3).

[31] Approximately 90 seconds are required for sucking the air and 30 seconds for analysis.

6.4. Methodology

The methodology applied in this study is twofold. First, a novel scanning cost approach is developed to estimate the total costs experienced by all actors involved under a specific scanning scenario and at a particular terminal and port. This analysis calculates the total costs from various components in each determined scenario.

The second part of the methodology is the supply chain impact analysis in which the generalized chain cost for maritime trade routes between Asia, the Middle East, and South America on the one hand and Europe on the other hand is evaluated. An extension of the CCM (see chapter 3) is applied. As the transport time is a crucial element of the generalized cost, the time related to the port scanning process and the transport time for the entire transport chain has been considered. Each part of the methodology will be explained in detail in the following sections.

6.4.1. Scanning Cost Approach

As the second part of the methodology, a new cost calculation model was developed to evaluate the operational scanning cost in different locations and scenarios. Some common parameters are applied throughout the calculation and initially plotted in Table 6.5.

Table 6. 5: Common cost elements

Parameter	Value and unit of measurement	Reference
Number of operational days in a year	*264 Days*	*Data collection*
Number of working hours in a day	*16 Hours*	*Interview with Belgian Customs*
Number of shifts in a day	*2*	*Interview with Belgian Customs*
Number of working hours in a shift	*8 Hours*	*Interview with Belgian Customs*

All the cost components considered in the calculation are explained in each scenario.

6.4.1.1. Estimation of the total number of scanned containers

The total number of containers is calculated as follows:

$N_{\text{total}} = N_{\text{handled container}} * \text{Share of } N_{\text{Unloading container}} * \text{Shipment factor} * \text{Means of transport factor}$

(Eq. 6.1)

In which:

- $N_{\textit{handled container}}$ = The total number of managed containers at the port of Antwerp in 2018 [TEU/year].
- *Share of* $N_{\textit{Unloading container}}$ = The number of imported TEUs in the Port of Antwerp in 2018 [TEU/year]. The unloading rate at this port is 44%, while the loading rate is 56% (Annual report 2019).
- *Shipment factor* = In the calculation, only the volume of non-transshipment cargo is taken into account, which is 42% at the port of Antwerp. This value means that the port Antwerp is the destination of 42% of all the imported goods.

– *Means of transport factor* = Cargo can be transported from port to the final destination by either road, rail, or inland waterway; however, in this chapter, only road transport, hence, the share of the truck, which is 52%, is considered.

6.4.1.2. Cost calculation process and cost components in Scenario 1:

In this scenario, the cost model is developed based on Equation 6.2, which evaluates the scanning cost per terminal.

$$Sce\ 1\ Cost = T_c + SO_c + SIA_c + PI_c + INV_c + Mai_c + Tr_c + HW_c + COM_{staff\ cost} + COM_{Hardware\ cost} + WT_c + DT_{cost\ for\ return} + Conces_c + Elec_c + Cab_c \qquad (Eq.\ 6.2)$$

The following sections explain each of the cost parameters.

$$Transition\ cost\ (T_c) = C_{travel\ GIP} * T_{travel} * N_{SC} \qquad (Eq.\ 6.3)$$

T_c = Transition cost from terminal to the scanning location

Table 6. 6: Cost components in T_c

Symbol	Cost component	Value and unit of measurement	Reference
$C_{travel\ GIP}$	*Travel cost to scanning location*	*50 EUR/(TEU*hour)*	*Interview with Belgian Customs*
T_{travel}	*Travel time to scanning location*	*1 Hour*	*Interview with Belgian Customs*
N_{SC}	*Number of scanned containers*	*TEU/year**	*Calculation*

** This value is obtained by multiplying the N_{total} obtained from Eq. 6.1 by 1% as the current scanning rate.*

$$Scanning\ Operation\ Cost\ (SO_c) = N_{person} * N_{shift} * N_d * GS * M \qquad (Eq.\ 6.4)$$

Table 6. 7: Cost components in SO c

Symbol	Cost component	Value and unit of measurement	Reference
N_{person}	*Number of persons involved for one scanner device*	*5*	*Interview with Belgian Customs*
N_{shift}	*Number of working shifts*	*2*	*Interview with Belgian Customs*
N_d	*Number of scanners*	*3*	*Interview with Belgian Customs*
GS	*Gross salary*	*2600 EUR/month*	*Interview with Belgian Customs*
M	*Number of months of the year*	*12*	-

Scanning Image Analysis Cost (SIA_c) $= N_{person} * N_{shift} * GS * M$ (Eq. 6.5)

Table 6. 8: Cost components in SIA c

Symbol	Cost component	Value and unit of measurement	Reference
N_{person}	*Number of image analyst*	*2*	*Interview with Belgian Customs*
N_{shift}	*Number of working shifts*	*2*	*Interview with Belgian Customs*
GS	*Gross salary*	*2600 EUR/month*	*Interview with Belgian Customs*
M	*Number of months of the year*	*12*	-

Physical Inspection Cost (PI_c) $= C_{PI} * N_{PC}$ (Eq. 6.6)

Table 6. 9: Cost components in PI_c

Symbol	Cost component	Value and unit of measurement	Reference
C_{PI}	*Cost of physical inspection*	*700 EUR/TEU*	*Interview with Belgian Customs*
N_{PC}	*Number of physically checked containers*	*5% of all the scanned containers (TEU/year)*	*Interview with Belgian Customs*

Investment Cost (INV_c) $= Inv_{yearly\ cost}$ (Eq. 6.7)

$Inv_{yearly\ cost}$ = Total investment cost of all the three scanners / Lifetime of the scanner (L_f)

Table 6. 10: Cost components in INV_c

Symbol	Cost component	Value and unit of measurement	Reference
$Inv_{total\ cost}$	*Total investment cost*	*11,424,336 EUR*	*Interview with Belgian Customs*
L_f	*The lifetime of the scanner*	*10 Years*	*Interview with Belgian Customs*

Maintenance Cost (Mai_c) $= Mai_{cost\ yearly}$ (Eq. 6.8)

Table 6. 11: Cost components in Mai_c

Symbol	Cost component	Value and unit of measurement	Reference
$Mai_{cost\ yearly}$	*The average yearly maintenance cost of all three scanners*	*431,991 EUR/year*	*Interview with Belgian Customs*

Training cost (Tr_c) = $Tr_{yearly\ cost}$ (Eq. 6.9)

$Tr_{yearly\ cost}$ = Yearly training cost is estimated by dividing the training cost by ten years (device lifetime).

Table 6. 12: Cost components in Tr_c

Symbol	Cost component	Value and unit of measurement	Reference
$Tr_{total\ cost}$	*Total training cost*	*25,410 EUR*	*Interview with Belgian Customs*
L_f	*The lifetime of the scanner*	*10 Years*	*Interview with Belgian Customs*

*Hardware cost (HW c) = C computer * N req,computer* (Eq. 6.10)

Table 6. 13: Cost components in HW c

Symbol	Cost component	Value and unit of measurement	Reference
$C_{computer}$	*Computer cost (cost of each computer needed for image analysis)*	*863 EUR/year*	*Based on the Dell Company website*
$N_{req,computer}$	*The number of required computers is equal to the number of image analysts*	*2*	*Interview with Belgian Customs*

Communication Process Cost (COM c) = COM staff cost + COM Hardware cost

There are two types of costs in the communication process: the first is for sending e-mails and notifications, and the second is for hardware cost (computers need).

$COM_{staff\ cost} = COM_{Staff\ required} * GS * M$ (Eq. 6.11)

$COM_{staff\ cost}$ = Staff cost for communication

Table 6. 14: Cost components in COM staff cost

Symbol	Cost component	Value and unit of measurement	Reference
$COM_{Staff\ required}$	*Number of staff required for communication process **	*2*	*Interview with Belgian Customs and calculation*
GS	*Gross salary*	*2600 EUR/month*	*Interview with Belgian Customs*
M	*Number of months of the year*	*12*	-

* *Based on an interview with Belgian Customs, in total, five different emails are sent for the entire scanning process for each container, by assuming that it takes three minutes for each email, thus based on calculation for every 64 containers per day (16 working hours), two persons are required (one person per shift).*

$$COM_{\text{Hardware Cost}} = C_{computer} * N_{req,computer} \quad \text{(Eq. 6.12)}$$

$COM_{\text{Hardware Cost}}$ = *The hardware cost for communication*

Table 6. 15: Cost components in COM Hardware cost

Symbol	Cost component	Value and unit of measurement	Reference
$C_{computer}$	*Computer cost (cost of each computer needed for communication)*	*863 EUR/year*	*Based on the Dell Company website*
$N_{req,computer}$	*Number of required computers **	*1*	*Interview with Belgian Customs and calculation*

** In this case, the total staff required for the communication process is divided by 2 to obtain the needed computers.*

Concession, electricity usage, and pipes and cable usage costs: Conces c + Elec c + Cab c (Eq. 6.13)

Based on obtained data from Belgian Customs, the annual average value for concession cost, power consumption cost, and cable usage cost is evaluated for each terminal in 2018. The original data is for the year 2010; then, by applying the Producer Price Index (PPI), the values are computed for 2018.

In this scenario, there are also some costs related to the opportunity cost or indirect cost, which mainly include the time lost and delay time for truck companies due to the scanning operation.

Waiting Time Cost due to scanning outside the terminal (WT c) (time lost cost)

This cost mainly applies to trucking companies that wait at the scanning location instead of moving to the final destination. This cost is computed according to the following equation:

$$(WT\ c) = C_{\text{travel destination}} * ([T_{SO} + T_{SIA}]) * N_{SC} \quad \text{(Eq. 6.14)}$$

WT c = Waiting time cost due to scanning outside the terminal (time lost cost)

Table 6. 16: Cost components in WT_c

Symbol	Cost component	Value and unit of measurement	Reference
$C_{\text{travel destination}}$	*Travel cost to the final destination**	*49 EUR/(TEU*hour)*	*Calculation*
T_{SO}	*Time spent on one scanning operation*	*0.083 Hour ***	*Interview with Belgian Customs*
T_{SIA}	*Time spent on scanning image analyzing for one container*	*0.25 Hour ****	*Interview with Belgian Customs*
N_{SC}	*Number of scanned containers*	*TEU/year*****	*Calculation*

** Based on teleroute.com the road transport cost is 0.82 EUR per km. Considering the truck's speed is 60 km/h, the distance transported for one hour is 60 km. By multiplying these two values, the travel cost for one hour is obtained as 49 EUR/(TEU*hour).*
*** As it was mentioned, the scanning operation takes 5 minutes.*
**** As it was mentioned, the image analysis takes 15 minutes.*
***** This value is obtained by multiplying the N_{total} obtained from Eq. 6.1 by 1% as the current scanning rate.*

Delay time cost for the return to the terminal and passing the gate out (DT cost for return)

This cost applies only to the current scenario where the scanning location is outside the terminal. Based on received data from Belgian customs, approximately 20% of scanned containers return to the terminal. Therefore, these containers have a delay time due to coming back to the terminal and passing the gate out for the second time. This cost is calculated as follows:

$$(DT_{\text{cost for return}}) = C_{\text{travel destination}} * T_{\text{return}} * N_{SCR} \qquad \text{(Eq. 6.15)}$$

$DT_{\text{cost for return}}$ = Delay time cost for the return to the terminal and passing the gate out

Table 6. 17: Cost components in DT cost for return

Symbol	Cost component	Value and unit of measurement	Reference
$C_{\text{travel destination}}$	*Travel cost to the final destination*	*49 EUR/(TEU*hour)*	*Calculation*
T_{return}	*Average return time for each container to come back to the terminal + to pass one gate out **	*1.083 Hour*	*Interview with Belgian Customs and calculation*
N_{SCR}	*Number of return scanned containers*	*TEU/year ***	*Interview with Belgian Customs*

** It takes one hour to transit from the scanning location to the terminal. Based on an interview with Belgian customs, it takes five minutes for the truck to pass the gate out.*
*** This value is obtained by multiplying the total number of the scanned containers by 20%.*

6.4.1.3. Cost calculation process and cost components in Scenario 2

In this scenario, the cost model is developed based on Equation 6.16, which evaluates the scanning cost per terminal.

$$Sce\ B\ Cost = SO_c + SIA_c + PI_c + INV_c + Mai_c + Tr_c + HW_c + COM_{staff\ cost} + COM_{Hardware\ cost} + Conces_c + Elec_c + Cab_c \quad (Eq.\ 6.16)$$

The following sections explain each of the cost parameters.

Scanning Operation Cost $(SO_c) = N_{person} * N_{shift} * N_d * GS * M$ *(Eq. 6.17)*

Table 6. 18: Cost components in SO_c in scenario 2

Symbol	Cost component	Value and unit of measurement	Reference
N_{person}	*Number of persons involved for one scanner device*	*5*	*Data collection*
N_{shift}	*Number of working shifts*	*2*	*Interview with Belgian Customs*
N_d	*Number of scanners*	*X **	*Calculation*
GS	*Gross salary*	*2,600 EUR/month*	*Interview with Belgian Customs*
M	*Number of months of the year*	*12*	-

** The calculation indicates that for scanning 120 Containers [TEU per hour], one FS6000DV X-ray system is required. This x-ray system can scan each container in 30 seconds.*

Scanning Image Analysis Cost $(SIA\ c) = N\ person * GS * M$ *(Eq. 6.18)*

Table 6. 19: Cost components in SIA_c in scenario 2

Symbol	Cost component	Value and unit of measurement	Reference
N_{person}	*Number of image analyst*	*X **	*Calculation*
GS	*Gross salary*	*2,600 EUR/month*	*Interview with Belgian Customs*
M	*Number of months of the year*	*12*	-

** The time spent on image analyzing for each scanned container is 15 minutes. Similar to scenario 1, two analysts must interpret each image simultaneously. According to the calculation, four analysts are required for every 64 scanned containers per hour, meaning two persons per shift.*

Investment Cost $(INV_c) = Inv_{yearly\ cost} * N_d$ *(Eq. 6.19)*

$Inv_{yearly\ cost}$ = Total investment cost of the *FS6000DV scanner* / Lifetime of the scanner (L_f)

Table 6. 20: Cost components in INV_c in scenario 2

Symbol	Cost component	Value and unit of measurement	Reference
$Inv_{total\ cost}$	*Total investment cost*	*3,100,000 EUR*	*Data collection*

L_f	*The lifetime of the scanner*	*10 Years*	*Data collection*
N_d	*Number of scanners*	-	*Calculation*

*Maintenance Cost (Mai_c) = $Mai_{cost\ yearly}$ * N_d* *(Eq. 6.20)*

Table 6. 21: Cost components in Mai_c in scenario 2

Symbol	Cost component	Value and unit of measurement	Reference
$Mai_{cost\ yearly}$	*The yearly maintenance cost of the FS6000DV scanner*	*240,000 EUR/year*	*Data collection*
N_d	*Number of scanners*	-	*Calculation*

Training cost (Tr_c) = $Tr_{yearly\ cost}$ *(Eq. 6.21)*

$Tr_{yearly\ cost}$ = Yearly training cost is estimated by dividing the training cost by ten years (device lifetime).

Table 6. 22: Cost components in Tr_c in scenario 2

Symbol	Cost component	Value and unit of measurement	Reference
$Tr_{total\ cost}$	*Total training cost*	*30,000 EUR*	*Interview with Belgian Customs*
Lf	*The lifetime of the scanner*	*10 Years*	*Interview with Belgian Customs*

Other cost components such as hardware cost (*HW_c*), communication process cost (*COM c*), physical inspection cost (*PI_c*), concession, power consumption, and cable costs are estimated as explained in the section cost calculation process for scenario 1.

6.4.1.4. Cost calculation process and cost components in Scenario 3

As in this scenario, the FS6000DV scanner is applied as the same as in scenario 2; thus, the following cost components are evaluated as explained in the previous scenario: scanning operation cost (SO_c), scanning image analysis cost (SIA_c), investment cost (INV_c), maintenance cost (Mai_c), training cost (Tr_c). Besides, other cost components such as hardware cost (HW_c), communication process cost (COM_c), physical inspection cost (PI_c), concession, power consumption, and cable costs are estimated as explained in the section cost calculation process for scenario 1.
In this scenario, the cost model is developed based on Equation 6.22, which evaluates the scanning cost per terminal.

$$Sce\ C\ Cost = SO_c + SIA_c + PI_c + INV_c + Mai_c + Tr_c + HW_c + COM_{staff\ cost} + COM_{Hardware\ cost} + Conces_c + Elec_c + Cab_c + WT_c \qquad (Eq.\ 6.22)$$

However, a new cost parameter applies only to this scenario. The *time lost cost due to scanning at OCR* or *Waiting Time Cost (WT_c).* This time lost is an opportunity or indirect cost and includes time spent scanning itself and the image analysis.

This cost applies to trucking companies that wait at the OCR lane (scanning location) instead of moving to the final destination. This cost is computed according to the following equation:

$$WT_c = C_{travel\ destination} * ([T_{SO} + T_{SIA}]) * N_{SC} \qquad (Eq.\ 6.23)$$

Table 6. 23: Cost components in WT_c in scenario 3

Symbol	Cost component	Value and unit of measurement	Reference
$C_{travel\ destination}$	*Travel cost to the final destination **	*49 EUR/(TEU*hour)*	*Calculation*
T_{SO}	*Time spent on one scanning operation*	*0.008 Hour ***	*Data collection*
T_{SIA}	*Time spent on scanning image analyzing for one container*	*0.25 Hour ****	*Interview with Belgian Customs*
N_{SC}	*Number of scanned containers*	*TEU/year*****	*Calculation*

** Based on teleroute.com the road transport cost is 0.82 EUR per km. Considering the truck's speed is 60 km/h, the distance transported for one hour is 60 km. By multiplying these two values, the travel cost for one hour is obtained as 49 EUR/(TEU*hour).*
*** As the FS6000DV scanner is used, the scanning operation takes half a minute.*
**** As it was mentioned, the image analysis takes 15 minutes.*
***** This value is obtained by multiplying the N_{total} obtained from Eq. 6.1 by the scanning rate in each scenario.*

6.4.1.5. Cost calculation process and cost components in Scenario 4

In this scenario, the cost model is developed based on Equation 6.24, which evaluates the scanning cost per terminal.

$$Sce\ D\ Cost = INV_c + Mai_c + Tr_c + PI_c + Conces_c + Elec_c + Cab_c \qquad (Eq.\ 6.24)$$

In this scenario, all the cost components pertain to the device of electromechanical technique. The applied cost components into the calculation are as follows: (i) number of required devices for cranes, (ii) investment cost, (iii) maintenance cost, (iv) training cost (which is included in the purchase cost), and (v) physical inspection cost. Furthermore, there is no communication process cost (COM_c) in this scenario as air analysis is performed during the unloading process. In the following section, each of the mentioned cost elements is explained.

Required number of devices for cranes ($N_{req\ device}$)

Port of Antwerp is known for the high productivity of its container handling, with 40 moves per crane per hour (Annual report 2019). Therefore, to obtain $N_{req\ device}$, the following equation is used:

*$N_{req\ device}$ = Number of containers SHOULD BE tested [TEU/year] * / Number of containers CAN BE tested by one crane [TEU/year] ** (Eq. 6.25)*

** Based on actual data, this value is estimated.*
*** As there are 40 moves per crane thus, each crane that is equipped with one electromechanical device (headspace sampling and ion trap) can test 40 containers in one hour.*

$$Investment\ Cost\ (INV_c) = Inv_{yearly\ cost} * N_{req\ device} \qquad (Eq.\ 6.26)$$

$Inv_{yearly\ cost}$ = Total purchase costs of both headspace sampling and ion trap devices/Lifetime of the devices (L_f). The devices' training cost (Tr c) is also included in this cost element.

Table 6. 24: Cost components in INV_c in scenario 4

Symbol	Cost component	Value and unit of measurement	Reference
$Inv_{total\ cost}$	*Total purchase costs*	*125,000 EUR*	*Data collection*
L_f	*The lifetime of the devices*	*10 Years*	*Data collection*
$N_{req\ device}$	*Number of required devices*	*X **	-

** This value is obtained based on Equation 6.25.*

$$Maintenance\ Cost\ (Mai_c) = Mai_{cost\ yearly} * N_{req\ device} \quad (Eq.\ 6.27)$$

Table 6. 25: Cost components in Mai_c in scenario 4

Symbol	Cost component	Value and unit of measurement	Reference
$Mai_{cost\ yearly}$	*The sum of yearly maintenance cost of the devices*	*13,000 EUR/year*	*Data collection*
$N_{req\ device}$	*Number of required devices*	*X **	-

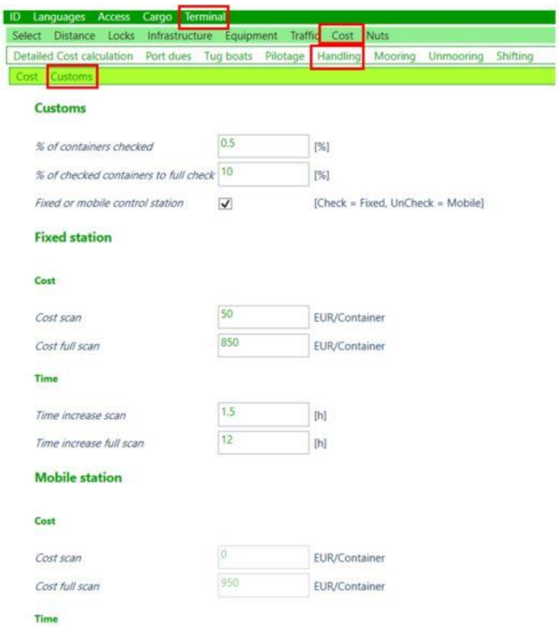
** This value is obtained based on Equation 6.25.*

Other cost components such as physical inspection cost (PI_c), concession, power consumption, and cable costs are estimated based on the cost calculation process for scenario 1.

6.4.2. Supply Chain Impact Analysis

The model explained in chapter 3 is extended with detail of the port container scanning and physical check process. Various options of scanning and screening are introduced, impacting each differently on staff and equipment needs and on-time consumption. In the section of *handling cost,* a new cost section called *customs costs* are added to the model.

Figure 6. 3: Updated CCM



In this section, the scanning rate and physical inspection rate of all the containers are assigned initially. Then, the relevant cost and time parameters are inserted based on choosing the fixed or mobile scanning process. Furthermore, a new maritime route: South America-EU, is incorporated into the model. The input data collection of the ports of the loop and the characteristics of each port are obtained based on the explained references and procedures in chapter 3.

The maritime trade route from South America to Europe is selected to assess the effect of scanning operations on the generalized chain cost. The origin port is the port of Santos, and the destination port is the port of Antwerp. The considered supply chain is plotted in Table 6.26.

Table 6. 26: Ports in the loop *

Loop	Ports in the loop
South America-Europe	Buenos Aires-Rio Grande-Navegantes-Santos-Bahia de Sepetetibal-Rotterdam-Bremerhafen-Antwerpen-Le Havre-Sines-Rio-Santos-Buenos Aires

* These routes are based on existing container loops

Besides, other details such as vessel size, fuel used inside and outside ECA, etc., are reported in Table 6.27.

Table 6. 27: Features of the vessel [32]

Property	Value	Property	Value
Vessel size (TEU)	5,466	Fuel Used In ECA	HFO + Scrubber
Installed power (kW)	24,680	Fuel Used Out ECA	HFO
Design speed (knots)	21.73	Fuel used of main engine (tons/hour)	4.58
Average payload ship (% of payload)	80	Type of engine	Diesel Engine

The results are obtained by calculating the vessel owner cost (EUR) and generalized chain cost (EUR/TEU) for the selected maritime route firstly without applying the scanning cost as the *reference situation*, while in the following scenario, the scanning costs are used at the port of Antwerp as the final destination.

[32] See chapter 5 for further details of calculation process of the values.

6.4.3. Sensitivity Analysis

AI is a promising technology that can significantly impact everyday life. AI can be beneficial in different fields and industries, such as machine learning, which helps image processing more quickly and efficiently. This research considers a sensitivity analysis by applying AI to image processing instead of the current manual image analysis. The objective is to assess the effect of AI on scanning operation and especially image processing from an economic perspective. In some scenarios, such as 2, 3, and 5, AI is considered the image analysis tool as in these scenarios, a scanning system is carried out, and therefore, AI is applicable for image processing, while in scenario 4, only air analysis is performed.

There are some cost parameters concerning the AI in which all of them are included as the investment cost. Consequently, it does affect the Scanning Image Analysis Cost (SIA_c) and Hardware cost (HW_c) for all the scenarios and Time lost cost due to the scanning or *Waiting Time Cost (WT c)* in some scenarios where applicable. Furthermore, the new value of the time parameter is incorporated in the CCM (see Figure 6.3).

Based on an interview with Belgium customs, some of the required components of AI are obtained. In this case, only one person is needed for image processing per container, while with the current manual analysis, two persons are involved for each container. Furthermore, the average time of image analysis is reduced from 15 minutes to only 5 seconds.

Table 6. 28: Cost elements of AI

Parameter	Value and unit of measurement	Reference
Average time for image analysis	*5 Seconds*	*Based on received data from Belgian Customs*
Number of image analysts for one scanned container	*1*	*Based on received data from Belgian Customs*
Yearly investment cost of AI ($Inv_{AI\ yearly}$)	*641,875 EUR*	*Based on received data from Experts*
Total investment cost of AI per 10 years	*6,418,750 EUR*	*Based on received data from Experts*

Therefore, it can be concluded that AI brings additional costs, considered investment costs; however, it reduces the image analysis time and the number of required image analysts. These values are considered in the calculations, and the obtained results are explained in the next section.

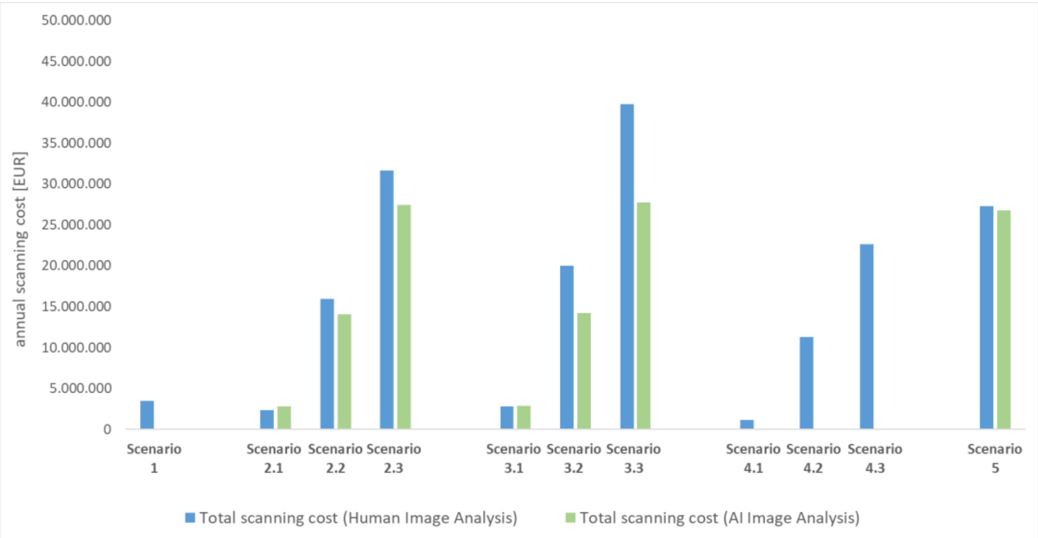
6.5. Results

The economic impact and supply chain costs are calculated for each scenario, respectively, based on the applied methodologies. The obtained results are explained into two parts; first, the total scanning cost in each scenario and the share of the cost components are plotted, and second, the generalized chain cost changes in each scenario are compared to current (base) scanning operation are illustrated.

6.5.1. Results of economic impact analysis

In the following sections, the total annual cost of scanning with (i) human image analysis and (ii) the cost of image processing with AI (sensitivity analysis) are reported separately for each scenario. First, the annual scanning costs are plotted in one figure.

Figure 6. 4: Yearly scanning cost in each scenario

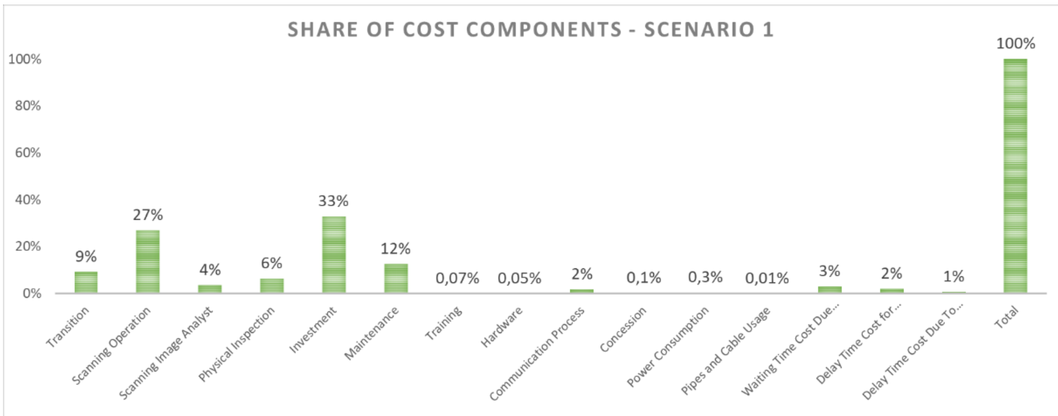


Rising the scanning rate leads to an increase in the costs of scanning. Comparing the results obtained for each scenario reveals that increasing the scanning rate would dramatically increase scanning costs. The most expensive scenario involves scanning at the gate out (scenario 3) relative to scanning at other locations.

6.5.1.1. Scenario 1

In scenario one, only manual image analysis is performed. The share of cost items compared to the total cost is plotted in Figure 6.5.

Figure 6. 5: The ratio of cost components in scenario 1



The investment and scanning operation costs have the highest share among all the components. Besides, transition cost to the scanning location is considered a decisive factor in the total cost.

6.5.1.2. Scenario 2

In scenarios 2 and 3, with a 5% scanning rate, the scanning operation with human image analysis shows the lowest cost. However, as the scanning rate increases (50% and 100%), the scanning cost with human image analysis rises dramatically, and AI scanning operation is a better option by showing the lower cost. It can be concluded that AI could be considered the best type of image processing if the scanning rate is at least 20% of the imported containers if the scanning location is inside the terminal and a minimum of 6% if the scanning location is at the gate out.

Table 6. 29: Number of required scanners and image analysts in scenario 2

Scenario 2	N_d (Number of Scanners)	N_{person} (Number of Image Analysts in manual image processing)	N_{person} (Number of Image Analysts in AI image processing)
5% of Total Containers	1	8	2
50% of Total Containers	1	80	2
100% of Total Containers	2	156	2

To have a comprehensive overview of the share of cost components in scenario two, the physical inspection cost is excluded from realizing which other cost parameters significantly impact the total cost. Figures 6.6 and 6.7 display this ratio for manual and AI image analyses, respectively.

Figure 6. 6: Ratio of cost components in scenario 2 – Manual image processing

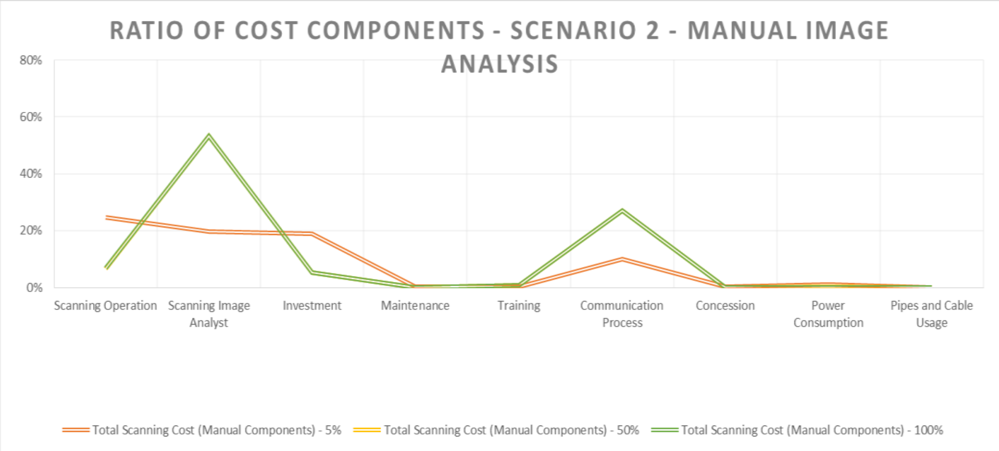
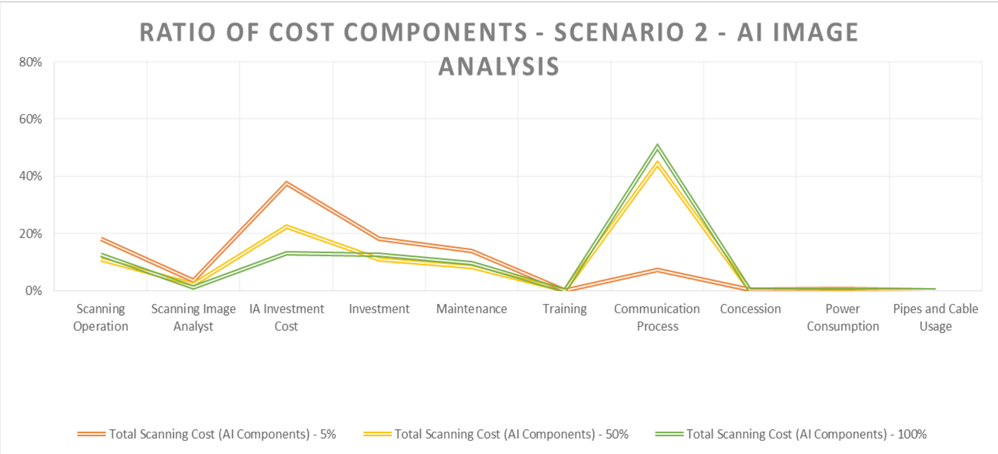


Figure 6. 7: Ratio of cost components in scenario 2 – AI image processing



As can be seen, in the case of 50% and 100% scanning rates, the majority of the cost (53% of the total cost) belongs to the image analyst cost in the manual image processing, while the communication process ranks in the second place by showing roughly 27% share.

By applying AI for image processing, different results are obtained. First, AI is not worth using in 5% of the scanning rate as its cost is the greatest. On the other hand, by increasing the scanning rate, the scanning cost diminishes notably, and AI shows the best result. Furthermore, the cost related to the communication process covers 50% of the total cost when the maximum rate is at its highest.

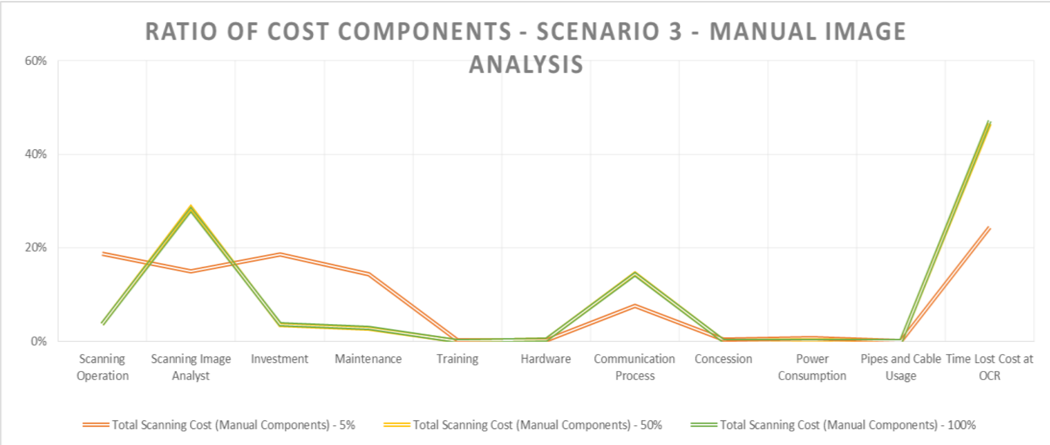
It is observed that, in the manual image analysis, the majority of the total cost pertains to the scanning operation, image processing, and investment costs. By increasing the scanning and since more staff is required for image analyzing thus, the share of image analysts cost has risen.

However, in the sensitivity analysis by AI, the image analysts' cost has dwindled dramatically. AI investment cost plays a vital role in the total cost, and by increasing the scanning rate, the share of this cost will be declined.

6.5.1.3. Scenario 3

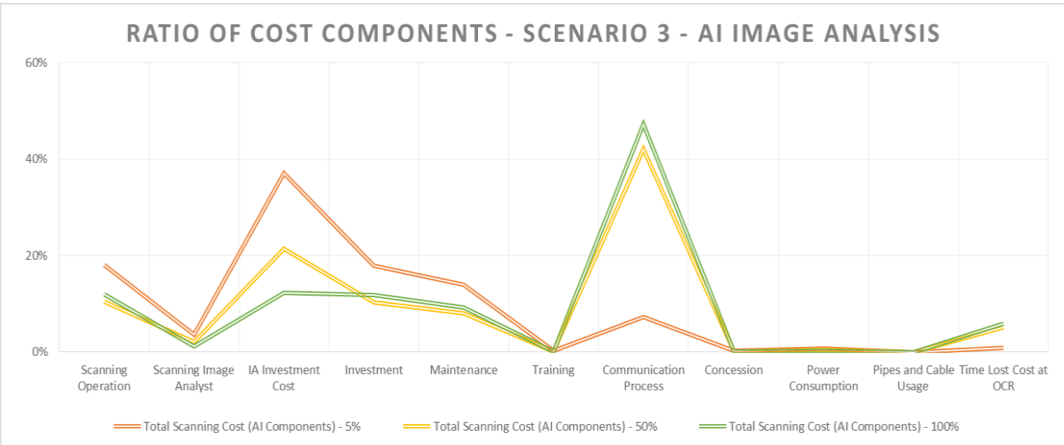
In this scenario, the scanning operation is performed at the OCR lanes at the gate out. The calculated results for manual and AI image processing are plotted in the following Figures.

Figure 6. 8: Ratio of cost components in scenario 3 – Manual image processing



At the scanning rate of 5%, the scanning operation cost, investment cost, and time lost cost have the most significant shares. The image analyst cost, communication process, and time lost costs rise considerably by maximizing the scanning rate.

Figure 6. 9: Ratio of cost components in scenario 3 – AI image processing



In the sensitivity analysis, the image analyst cost dwindles drastically as fewer staff is required. Furthermore, AI investment has the highest share in the case of 5% of scanning rate; however, by increasing the scanning rate, this cost-share experiences a massive decline, which confirms that AI is worth applying if the scanning rate is high. Interestingly, the time lost cost is reduced remarkably compared to manual image processing.

Table 6. 30: Number of required scanners and image analysts in scenario 3

Scenario 3	N_d (Number of Scanners)	N_{person} (Number of Image Analysts in manual image processing)	N_{person} (Number of Image Analysts in AI image processing)
5% of containers	1	8	2
50% of containers	1	80	2
100% of containers	2	156	2

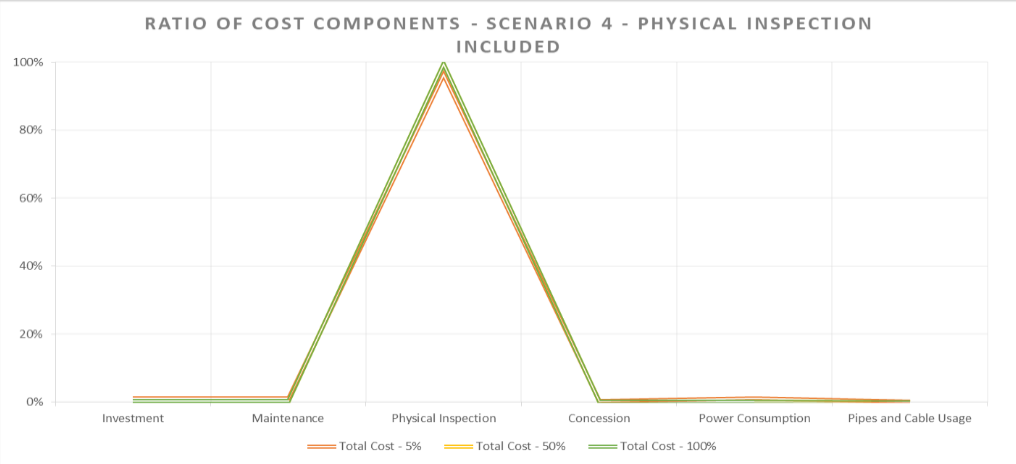
6.5.1.4. Scenario 4

In scenario 4, given that only ion trapping technique and headspace sampling are performed, and there is no cost related to scanning operation, image analysis, and investment, the scanning cost is significantly lower than scenarios 2 and 3. Based on Eq. 6.25, the required devices (*$N_{req\ device}$*) for each sub-scenario are calculated.

Table 6. 31: Number of required devices in scenario 4

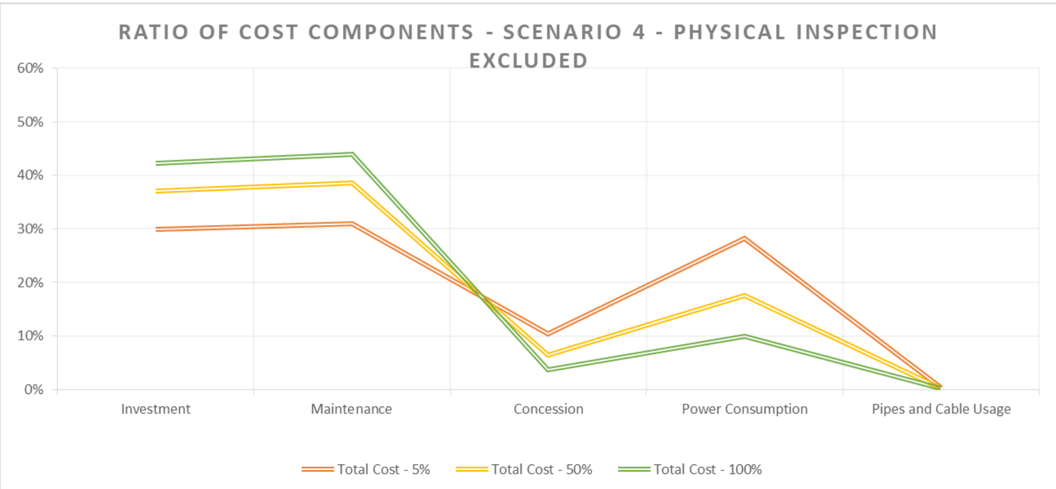
	Testing Rate		
Scenario 4	5% of containers	50% of containers	100% of containers
$N_{req\ device}$	1	2	4

Figure 6. 10: Ratio of cost components in scenario 4 – Physical check included



As can be seen, the majority of the cost belongs to the physical check (96% in 5% scanning rate, 99% in 50%, and 100% scanning rates), and other cost elements cover less than 5% of the total cost. To better understand the share of different cost components, the physical inspection cost is excluded in Figure 6.11.

Figure 6. 11: Ratio of cost components in scenario 4 – Physical check excluded



As more testing devices are needed by increasing the scanning rate, the investment and maintenance costs grow accordingly.

6.5.1.5. Scenario 5

Scenario 5, which combines headspace sampling and ion trapping with scanning at the terminal gate out, displays the lowest annual costs compared to other possible future scenarios. In this scenario, all containers are inspected using headspace sampling and ion trapping on the crane, followed by additional scanning of suspicious containers at the gate out (assumed to be 10%). In this case, the rate of physical verification is reduced compared to scenarios 2.3 and 3.3, which reduces total annual costs.

Table 6. 32: Annual scanning cost in scenario 5 – Manual image analysis

	100% of testing rate with headspace sampling	10% of scanning rate at the gate out	
Cost items	Total scanning cost (*EUR*/year)	Cost items	Total scanning cost (Manual Image Analysis - *EUR*/year)
Investment	€50,000	Scanning Operation	€312,000
Maintenance	€52,000	Scanning Image Analyst	€499,200
Physical Inspection	€22,498,665	Physical Inspection	€2,249,866
Concession	€4,380	Investment	€310,000
Power Consumption	€11,834	Maintenance	€240,000
Pipes and Cable Usage	€176	Training	€3,000
		Hardware	€6,904
Total cost	**€22,617,055**	Communication Process	€253,052
		Concession	€4,380
		Power Consumption	€11,834
		Pipes and Cable Usage	€176
		Time Lost Cost at OCR	€813,702
		Total cost	**€4,704,114**

AI image processing is applied in the sensitivity analysis instead of manual image analysis. The results are plotted in Table 6.33.

Table 6. 33: Annual scanning cost in scenario 5 – AI image analysis

	100% of testing rate with headspace sampling	10% of scanning rate at the gate out	
Cost items	Total scanning cost (*EUR*/year)	Cost items	Total scanning cost (AI Image Analysis - *EUR*/year)
Investment	€50,000	Scanning Operation	€312,000
Maintenance	€52,000	Scanning Image Analyst	€63,263
Physical Inspection	€22,498,665	IA Investment Cost	€641,875
Concession	€4,380	Physical Inspection	€2,249,866

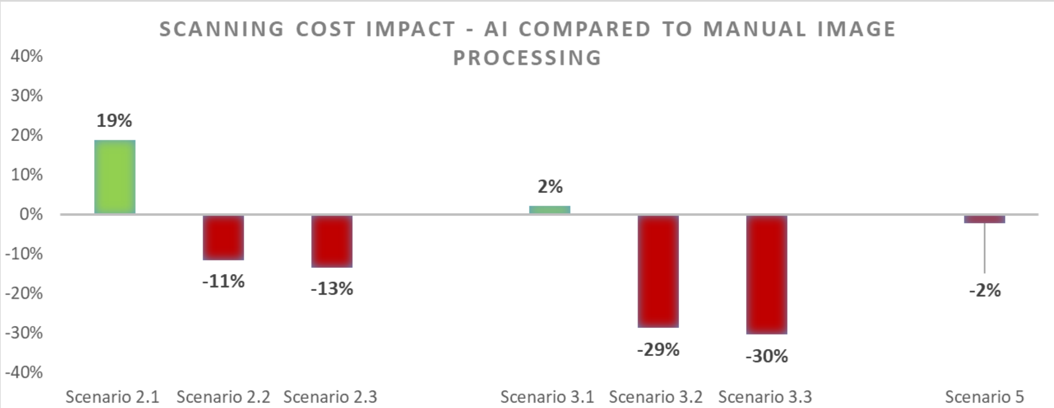
Power Consumption	€11,834	Investment	€310,000
Pipes and Cable Usage	€176	Maintenance	€240,000
		Training	€3,000
Total cost	**€22,617,055**	Communication Process	€253,052
		Concession	€4,380
		Power Consumption	€11,834
		Pipes and Cable Usage	€176
		Time Lost Cost at OCR	€30,623
		Total cost	**€4,120,070**

By comparing Tables 6.32 and 6.33, it is observed that image analysts and time lost cost at the OCR lanes greatly influence the total cost in the manual image processing. On the other side, by applying AI, these two costs are reduced significantly due to two key reasons: (i) fewer image analysts are required and (ii) less time is needed for the result of image processing, and consequently, less time will be spent at the gate out. However, the AI investment cost is introduced in this case which plays a significant role in the total cost.

6.5.1.6. The effect of AI on the scanning cost

The scanning cost calculation process was repeated to figure out the effect of AI on image processing. In this case, instead of manual image processing, AI has been applied. Figure 6.12 illustrates the cost-saving of AI compared to the manual image processing in each scenario.

Figure 6. 12: Percentage of AI compared to manual image analysis



It is observed that AI is worth applying if the scanning rate is either 50% or 100%. However, in the case of a 5% scanning rate regardless of the scanning location, AI does not provide an economical option.

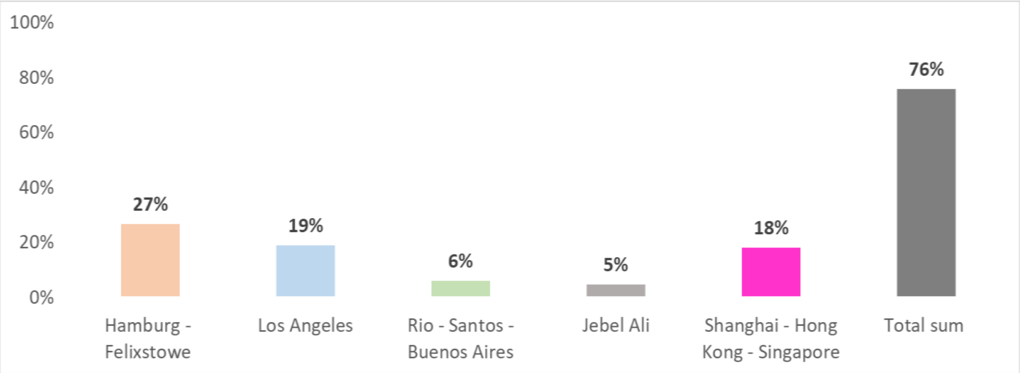
Based on the results, AI is worth using in the case of a high scanning rate, and it is observed that AI presents lower scanning costs. Thus, it can be concluded that AI is considered a better option by maximizing the scanning rate.

Implementing AI for image analysis would decrease the number of image analysts required, drastically diminishing scanning costs related to manual image processing, with an average economic cost reduction of about 9%. The cost reduction is much smaller in terms of impact on the supply chain and can be negligible.

6.5.2. Results of the supply-chain impact analysis

The adjusted CCM was applied to determine the economic influence of scanning operation on the generalized chain. The following ports are selected for preparing the chain impact analysis: Buenos Aires, Rio, Santos (South America), Felixstowe, Hamburg (Europe), Hong Kong, Shanghai, Singapore (Far East), Jebel Ali (Middle East), and Los Angeles (North America). With the inclusion of the selected ports, the analysis covers 76% of all TEUs handled at the Port of Antwerp at the continental level. In statistical terms, this is highly representative of the total volume of containers arriving at the Port of Antwerp.

Figure 6. 13: TEUs handled at the Port of Antwerp at the continental level



Source of data: Port of Antwerp

The destination port for each origin port listed above is the Port of Antwerp. The size of the vessel is 5,466 TEU for all maritime routes. The results obtained for each origin-destination route are illustrated in the figures below.

6.5.2.1. South American Ports to Antwerp:

Three origin ports in South America are taken into account in the maritime route to Antwerp

Figure 6. 14: Generalized chain cost from Buenos Aires to Antwerp

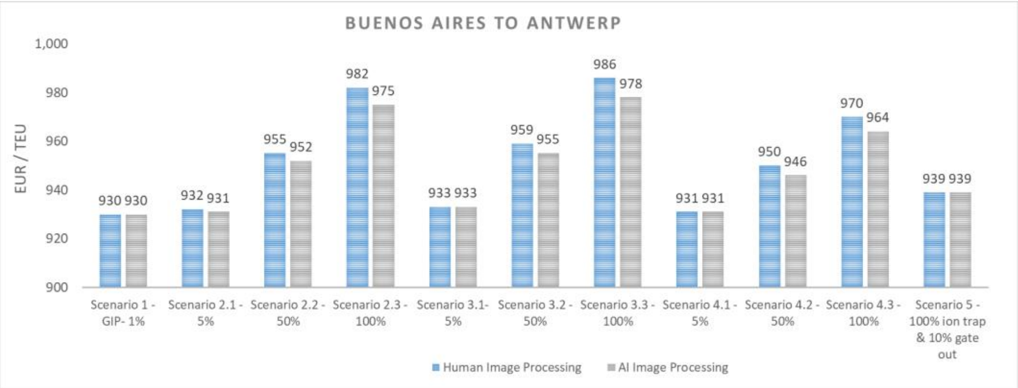


Figure 6. 15: Generalized chain cost from Rio to Antwerp

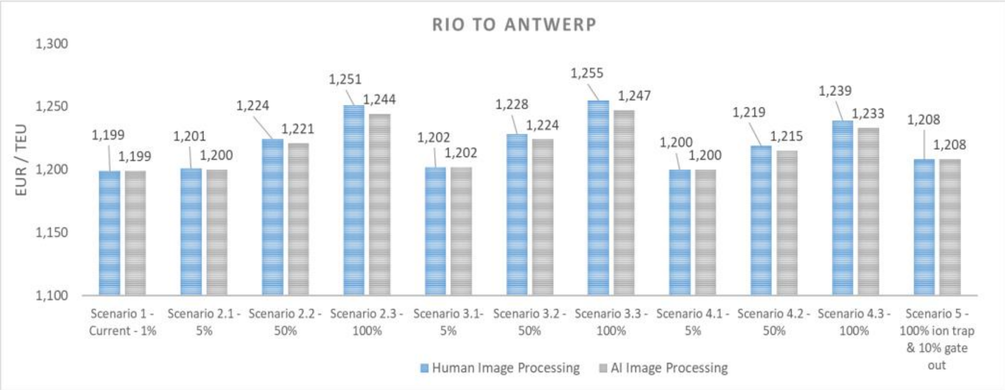
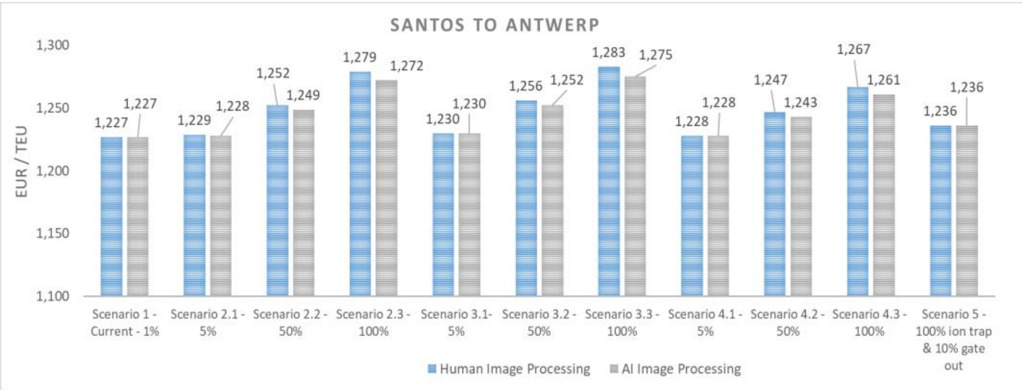


Figure 6. 16: Generalized chain cost from Santos to Antwerp



The obtained results for each of these ports reveal that the generalized chain cost would grow by increasing the scanning rate. Moreover, scenario 5 displays better results compared to the other scenarios.

The findings depict that the scanning rate plays a significant role in each scenario. Furthermore, scenarios 3 and 2 are considered the most costly options for each origin-destination pair, respectively.

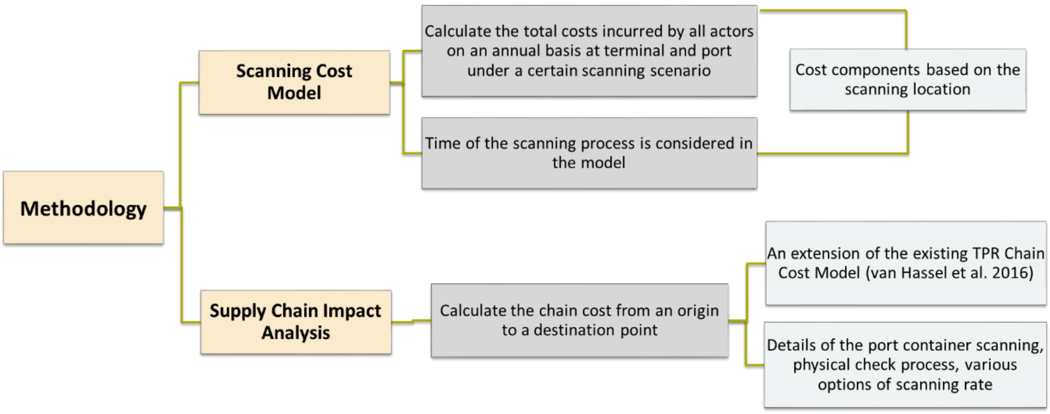
Similar outcomes are obtained for other regions heading to the port of Antwerp, which are plotted in Appendix C.

On the other hand, the effect of AI on the supply chain cost is insignificant. By comparing the generalized chain cost of manual and AI image processing, it is noticed that the outcomes do not differ considerably.

6.6. Generalization of the scanning cost approach

Importantly, this research develops a novel scanning cost approach based on multiple scanning rates and locations used worldwide. This model considers different cost components in the calculation, and the time of applying each cost component (where relevant) is taken into account. Figure 6.17 illustrates the model's general overview and the adjusted version of the available CCM.

Figure 6. 17: Methodology of the cost scanning approach



The cost components related to each scanning location and based on the applied technology are plotted in Table 6.34.

Table 6. 34: Cost components of each scenario

	Scanning location and technology			
Cost Component	Central scanning location inside the terminal (X-ray system)	OCR lanes at the gate out (X-ray system)	Air analysis on the crane (Headspace sampling and ion trapping)	Type of cost
Scanning operation cost	x	x	-	Direct
Scanning image analyst cost	x	x	-	Direct
Physical inspection cost	x	x	x	Direct
Investment cost	x	x	x	Direct
Maintenance cost	x	x	x	Direct
Training cost	x	x	x	Direct
Hardware cost	x	x	-	Direct
Communication process cost	x	x	-	Direct
Concession cost	x	x	x	Direct
Pipes usage cost	x	x	x	Direct
Electricity usage cost	x	x	x	Direct
Waiting Time Cost Due to Scanning - Time Lost Cost	x	x	-	Indirect

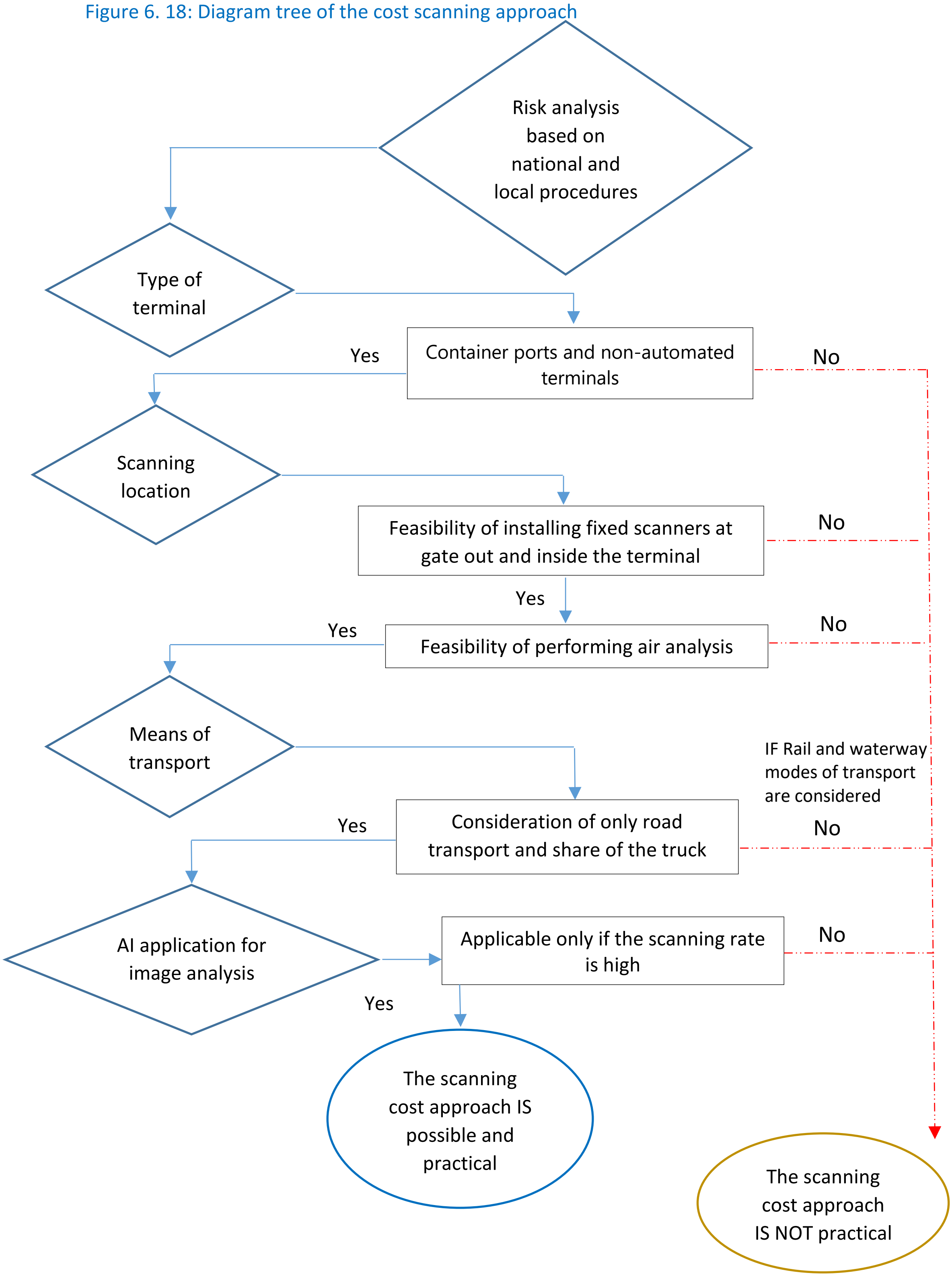
In the case of applying AI for image analyzing:				
AI Investment cost	x	x	-	Direct

The formulas and developed model could be applied in other ports across the globe by taking the following considerations:

- The scanning locations are defined after scrutiny of several factors based on the properties of the terminal, such as automation, container terminal, the feasibility of installing fixed scanners, etc.; thus, these factors should be checked to apply the exact scanning locations which have been used in this research.
- The model is not applicable in automated terminals due to specific cargo handling operations.
- The national and local risk analysis procedures before scanning should be considered along with the communication process approach.
- Road transport is the desirable means of transport. As the model does not consider rail or waterway systems, data regarding the share of the truck needs to be provided.

Figure 6.18 illustrates the scanning cost approach based on a diagram tree.

Figure 6. 18: Diagram tree of the cost scanning approach



6.7. Conclusion

International trade is growing rapidly, focusing on supply security and trade facilitation, resulting in fast changes in customs officials' roles. Besides, with the rise of global threats, customs play an increasingly important role in guaranteeing the security of external borders and supply chains, leading to enhanced security.

This chapter focuses on illicit trafficking in the Port of Antwerp, causing severe social and security threats. It coincides with an increase in container throughput volumes. The increase in international trade, primarily through container transport, has been accompanied by the rise in various types of smuggling, including narcotics, weapons, cigarettes, explosives, and radioactive and nuclear substances, along with all possible risks and threats associated with these activities. The main focus of this study is on narcotics, although it also addresses the potential of the researched technologies to help detect other sources of threat.

The addressed research questions were: (i) *what is the total cost of scanning the containers for the actors involved under various scanning percentages/rates at the terminal level? and (ii) how will the generalized chain cost change under the increasing scanning rate for the defined maritime routes from several ports in different continents to the port of Antwerp?*

In this chapter, five main scenarios with increasing the scanning rate for container terminals are tested in an economic impact and supply impact analysis, namely, scanning at the scanning location outside the terminal (Scenario 1), scanning at a central scanning location on the terminal (Scenario 2), scanning at the terminal gate out (Scenario 3), testing the container with headspace sampling (Scenario 4) and a combination of 100% headspace sampling and ion trapping, 10% scanning at the gate out (Scenario 5).

The study indicates that technology can positively affect current processes to enhance the supervision of the container supply chain. From a technological point of view, three types of technology domains are considered in this study: imaging via X-ray system, electromechanical techniques, and AI.

The three selected technologies and their combinations were chosen for the economic feasibility and supply chain-impact analyses. Extending the current solution with more transport to the scanning location is not an option, given the sharp increase in costs that it would entail. Headspace sampling and ion trapping alone would increase costs as well. More importantly, however, this option suffers from a high incidence of false positives, thus leading to a high rate of manual inspections. It has therefore been observed that no individual technological domain has the lowest cost impact, which can nevertheless be obtained by combining several different specialized fields.

The findings indicate that the lowest costs are associated with scenario 5. Moreover, the results obtained demonstrate that increasing the scanning rate at the Port of Antwerp would raise the scanning costs for the terminal. The costs would be significantly higher than the current situation, particularly for the large container terminals (due to the higher number of handled containers). Furthermore, congestion at the terminal and delays in the operational process are essential issues that must be addressed.

In the results, distinctions can be made amongst the various scenarios. For the container terminals, the lowest cost increase relative to the current situation (with a scanning rate of 1%) in terms of both economic and supply chain impact is found in scenario 5 (it should be noticed that scenario 4 is not a scanning process and only air analysis is performed). This fact is more highlighted in comparison with manual image processing.

Even in this scenario, however, the economic impact exceeds the current situation by a factor of 8. Besides, scenario five is associated with the lowest supply-chain impact of all alternatives. In scenario 2.3 (with a 100% scanning rate), the scanning cost is factored by nine compared to the reference scenario, while, in scenario 3.3, this value is equal to 11.

Implementing AI for image analysis would decrease the number of image analysts required, drastically diminishing scanning costs related to manual image processing, with an average economic cost reduction of about 9%. The cost reduction is much smaller in terms of impact on the supply chain and can be negligible.

It is observed that AI is worth applying if the scanning rate is either 50% or 100%. However, in the case of a 5% scanning rate regardless of the scanning location, AI does not provide an economical option.

Chapter 7: Supply chain analysis and economic assessment of the transportation of dry and reefer cargo in the West-Africa-Europe trade route

7.1. Introduction

The port choice selection plays a significant role in the MarSC. The choice of shipping route for unitized goods is a complex process involving many attributes of different actors and services (Tavasszy, Minderhoud, Perrin, & Notteboom, 2011). Besides, shipping routes can affect both the operational cost of carriers and the customer service level (Tran, 2011). The importance of choosing an optimal port for callings is paramount for shipping carriers to reduce their total transportation costs (Zavadskas, Turskis, & Bagočius, 2015).

Understanding existing drivers of port choice and the substitutability between nodes within the network is vital for informing policy decisions regarding the allocation of often scarce resources in developing capacity (O'Connor et al. 2020).

Due to the growing demand for perishables worldwide and shifts of existing trade from other modes, the reefer container market is increasing and draws lots of attention (Castelein et al. 2020). Fruits and vegetables are generally quite sensitive to atmosphere and temperature variations, which means that the container's cargo temperature and air composition must be kept within certain limits (Sørensen et al. 2015). The reefer container market is characterized by the need for continuous temperature control of container cargo (Castelein et al. 2020).

The objectives of this chapter are two folds, starting from a case featuring fresh produce from West Africa to Europe. First, to figure out the ports in the West-Europe region based on the port choice factor of the highest potential container flow that can be called at in the specific round trade route from West-Africa-Europe.

The three selected ports in this chapter are located in the same region. Port of Antwerp is considered the main port of call for dry and reefer cargo in this trade route by handling more than 50% of loading cargo in the return leg. Moreover, Rotterdam and Flushing ports provide an economic comparison in the West Europe region with Antwerp's port to select the best central hub in terms of lowest maritime and supply chain costs. The objective is to choose the main port of call in the West Europe region, which can also be used for transshipment cargo from/to other ports.

Second, to evaluate the maritime and supply chain costs for the mentioned trade according to various scenarios based on the (non) transshipment cargo types, different types of the commodity (dry and reefer), and the combination of different (un)loading ports in Europe, the UK, and other regions namely Baltic, Northern part of the North Sea, and Ireland. This research considers the whole supply chain segments, including hinterland leg, port section, and maritime route, to evaluate the economic impact of port choice selection in this trade route.

Port selection and supply chain optimization analyses are carried out by seeking the following research questions:

- *Which of the three ports of Antwerp, Rotterdam, and Flushing will be the main port of call in North-West-Europe?*

- *What is the economic influence of calling at more ports (than the selected ports among Antwerp, Rotterdam, and Flushing) on the vessel owner and the supply chain costs of transporting cargo for the trade route West-Africa-Europe?*

The focus of this study is the supply chain of reefer, and dry container flows in the West Africa-Europe trade route. Four African ports, namely Tema (Ghana), Douala (Cameroon), Abidjan (Ivory Coast), and Dakar (Senegal), are considered in the loop in which both types of dry and reefer cargoes are taken into account.

To attain the goals of this chapter, initially, a data collection approach is used to obtain the relevant container flow for major European ports with the destination of West-African ports. Subsequently, based on the gathered data, the CCM (see chapter 3) is applied as the methodology to calculate the ship's total cost and supply chain cost in the West-Africa-Europe route.

Furthermore, this study encompasses the economic and environmental dimensions of sustainability of MarSC as in this research, the ECA regulations to mitigate sulfur emission of the ship are taken into account by applying MDO inside ECA while outside ECA HFO is consumed.

Table 7. 1: Major EU ports in the loop

	Considered ports
EU ports	Antwerp, Rotterdam, Flushing, Zeebrugge, Le Havre, Brest, Montoir de Bretagne, Vigo, Marin, Lisbon, Sines

The remaining of this chapter is organized as follows. Section 7.2 explains the literature review on the port selection criteria and supply chain cost, while section 7.3 discusses the data collection method and applied methodology. Section 7.4 provides the calculation process, scenario development, and obtained results, and the overall findings and conclusions are described in section 7.5.

7.2. Literature review

The literature review section is categorized into three sub-sections. The first one provides a general overview of the port choice determinants and port selection criteria and processes from various port users. The second and third sub-sections report a brief discussion regarding supply chain cost, reefer, and inland transport.

7.2.1. Port choice and port selection process

The research on the port selection process and determinants are investigated extensively in the literature. This section explains some of the primary studies. The research includes the port choice criteria from port users' and port service providers' perspectives. Several studies in the literature have used the AHP to analyze port competitiveness and attractiveness to users (Andrew Yuen et al. 2012). Seo and Ha 2010 investigate the port size and level of incentives administered in the port selection process of the port users. Tavasszy et al. 2011 promote a strategic choice model for container shipping routes by considering port selection criteria. Lam and Dai 2012 developed a port selection model based on port clusters serving a specific market.

In the context of port competition, there has been increasing cooperation between firms involved in the intermodal transport chain, including seaport services (Álvarez-SanJaime et al. 2015). Malchow and Kanafani 2004 use a discrete choice model to assess the competition between ports. The main findings show that the oceanic and inland distances variables have the most significant impact on carriers' distribution of shipments, followed by port location, and the choice behavior process varies across both carriers and commodities.

Andrew Yuen et al. 2012 explore the relative importance of factors that influence a container port's competitiveness, including capacity availability and the size and hinterlands connectivity. The results show that port location is the most critical factor for both forwarders and shippers in determining port competitiveness, while port costs are crucial for shipping liners. Furthermore, De Oliveira and Cariou 2015 inquire about the effects of inter-port competition on port efficiency and examine the degree of competition assessed at different levels (local, regional, and global level). The results show that increasing competition mitigates port efficiency when measured at the regional level. In recent research, Rezaei et al. 2018 indicate that transport costs and times along the transport chain are the dominant factors for port competitiveness. The other essential elements are satisfaction, reputation, and flexibility.

Steven and Corsi 2012 study the price and port productivity in the seaport selection decision. Bagočius et al. 2013 and Zavadskas et al. 2015 introduce a Multi-Criteria Decision Making (MCDM) model to establish a deep seaport in the Klaipeda port in Lithuania to improve economic demands. Puig et al. 2014 inquire about the determination and selection of Environmental Performance Indicators (EPIs) for sustainable port management in European ports and the capacity for Port Authorities to adopt and implement them.

Notteboom et al. 2017 investigate the relationship between port choice of alliance members and the direct involvement of shipping lines in container terminals in North-West European ports. Besides, Baert and Reynaerts 2020 investigate the determinants affecting the attractiveness of the ports in the

United States. The results reveal that port charges and port congestion are vital factors in the decision-making process of port users. O'Connor et al. 2020 develop an application of port demand modeling to examine behavioral patterns affecting demand for port services in the Irish port network.

In the context of dry port selection criteria, Rodrigues et al. 2020 provide a literature review on the determinants of dry port criteria and decision processes in which the decisive factors are categorized as follows (i) cost factors, (ii) location, installation, and infrastructure factors, (iii) accessibility factors, (iv) operational factors, (v) social and policy factors, and (vi) environmental factors. Talley and Ng 2020 demonstrate the determinants of the port service providers to select a port from a chain perspective. Hsu et al. (2020) assess the port choice of liner carriers for ship calls. The results indicate that port choice factors with higher importance for liner carriers are cargo volume (local cargo volume, transit cargo volume, and import/export cargo balance) followed by terminal handling charges and port dues. Furthermore, port managers must satisfy carriers' demands in port choices (Hsu et al. 2020).

In summary, Table 7.2 illustrates the objectives, perspective, and results of other research on identifying the most critical factors in the port choice process in different ports.

Table 7. 2: A literature review on port choice criteria

Reference	Objective	Results
Ugboma et al. 2006	To investigate the most critical factors of the port selection process in four ports in Nigeria. Shippers' perspective	Port efficiency, frequency of ship visits, and adequate infrastructure are the dominant factors, while the quick response to port users' needs is the least important criteria. Other identified factors are location, port charges, and reputation for cargo damage.
Young-Tae Chang et al. 2008	To investigate the factors influencing shipping companies' port selection process. Trunk liners and feeder service providers viewpoints	The results rank six essential variables, namely (i) local cargo volume, (ii) terminal handling charge, (iii) berth availability, (iv) port location, (iv) transshipment volume, and (v) feeder connection.
Tongzon 2009	To evaluate the factors influencing port choice in Southeast Asian Freight forwarders' perspective	The most crucial factor is port efficiency, followed by shipping frequency, adequate infrastructure, good geographical location, low port charges, quick response to port users' needs, and reputation for cargo damage.
Tran 2011	To investigate the optimal port selection process in liner shipping. Logistics perspective with the combination of several parameters such as ship cost, port tariff, inland transport cost, and inventory cost to optimize/minimize the total transportation cost in cargo's journey (sea cost and inland cost).	The decrease in port calls can reduce ship, inventory, and port tariffs, leading to higher inland/feeder transport costs.

Nazemzadeh and Vanelslander 2015	To determine the most significant factors impressing the port selection process for North-European ports. Shippers, carriers, and freight forwarders	Port costs have the most critical effect in the port selection process for all three port users, including geographical location, quality of hinterland connections, productivity, and port capacity.
Abdul Rahman et al. 2019	To investigate the selection of ports of call in regular intra-regional container services between Malaysian ports and other Asian ports	This study provides a methodological framework that can assist maritime stakeholders in evaluating the feasibility and competitiveness of specific intra-regional port-to-port liner service configurations.
Talley 2019	To investigate port choices by port service providers. Port service providers, namely port operators, shipper agents (freight forwarder and third-party logistics provider), harbor pilots, tugboat operators, shipping line agents, and customs brokers	Determinants of port choices by port service providers are the payments or revenues that the providers receive from users of their provided cargo port services.

Source: Author's composition based on

It can be observed that the majority of researchers investigated the port selection process and criteria by different stakeholders in maritime shipping in all the ports around the world, such as Asian, African and North-European ports. The results reveal that port efficiency, port costs, and geographical locations are the most dominant factors in the port selection from port users, shippers, carriers, and freight forwarders. According to Tongzon (2009), port operators and authorities must prioritize improving their overall level of efficiency relative to other factors to attract more freight forwarders to use their ports.

7.2.2. Supply Chain Cost

Global supply chains depend critically on efficient information and product flows among the suppliers, manufacturers, distributors, and retailers in the chain, and a highly proficient transportation system acting as the attachment holds the entire system together (Steven & Corsi, 2012). It provides various benefits to the businesses and consumers, such as improvement in services, product innovation, efficiency, etc., and at the same time confronts different challenges caused by risks or uncertainties (He and Yin 2020).

The literature regarding supply chain contexts such as management, cost, sustainability, collaboration among stakeholders, etc., is extensive and has attracted both academia and practitioners' attention. This section reports some recent research on supply chain cost.

Saif-Eddine et al. 2019 investigate optimizing the total supply chain cost in the Inventory Location Routing Problem (ILRP) by adapting the Vendor Managed Inventory VMI strategy. In the context of blockchain and its effects on the supply chain, Schmidt and Wagner 2019 apply transaction cost theory to understand the influence of blockchain as a prominent component of the digital transformation on supply chain relations. Moreover, blockchain enables more market-oriented supply chain relations.

Several researchers investigated the cost-sharing and price contracts between the upstream and downstream of the supply chain. To capture a two-echelon supply chain (an upstream manufacturer and a downstream retailer), Fan et al. 2020 investigate a two-stage game model by incorporating product quality, consumer disutility, and product liability cost into a market demand function. Furthermore, Yu et al. 2020 explore the collaboration mode of emission reductions in a low-carbon supply chain, including manufacturers and retailers. In similar research, Xiao et al. 2020 inquire about a two-echelon sustainable supply chain that consists of one supplier and one manufacturer and ask about the price commitment and cost-sharing contracts.

Firms tend to be cost-effective, and an increase in a firm’s cost can adversely affect the firm’s performance (He and Yin 2020). Liu et al. 2020 develop research on the optimal design of low-cost supply chain networks in a case study of a fast-moving consumer goods supply chain in East Asia. Additionally, He et al. 2020 investigate a low-carbon service supply chain consisting of a service provider who is accountable for emission reduction - and a service integrator - who is responsible for advertising - by considering three different cost-sharing contracts to assess the positive and negative features of the contracts in the presence of firms’ CSR behaviors.

Some of the leading developed research in the reefer container and inland transport are described in the following sub-sections.

7.2.2.1. Reefer transport

Ng and Gujar 2009 assess the spatial characteristics of inland transport hubs based on analytical evidence from the users’ choice of dry ports in Southern India and provide a platform on locational choice and the development of transport hubs and supply chains. In environmental sustainability, Liao et al. 2011 assess the CO_2 emissions from inland container transport in Taiwan.
Álvarez-SanJaime et al. 2015 investigate the stimulants to integrating port activities with inland transport services and its welfare implications under inter-ports competition. Furthermore, Chao and Chen 2015 developed a time-space mathematical model based on a micro view concept concentrating on precise reposition operations, which are more convenient for accommodating special containers such as reefer containers.

Defraeye et al. 2015 consider the ambient loading protocol for cooling citrus fruit during marine transportation in refrigerated containers to evaluate reefer containers' energy efficiency, energy-saving, and power consumption. To reduce the power consumption of refrigerated containers, Sørensen et al. 2015 suggest a Model Predictive Controller (MPC) with the potential energy savings at different ambient temperatures and fan control methods. Budiyanto and Shinoda 2020 explore the effect and energy saving of roof shade installation over storage yard in reefer container storage yard by Computational Fluid Dynamics (CFD) simulation method.

7.2.2.2. Inland transport

To determine whether the external costs and externalities can be used interchangeably in terms of policy decision-making, Merchan et al. 2019 provide updated values of externalities and external costs for inland freight transport for Belgium in 2012, considering three adverse impacts related to atmospheric change caused by human beings namely climate change, photochemical ozone formation, and PM formation by applying Life Cycle Assessment methodology. The results suggest that externalities and external costs should be used in a complementary way.
Kurtulus and Çetin 2020 examine the modal shift potential in a short distance (from the road to intermodal rail) in Turkey's inland container transport corridor by considering the behavioral aspects of inland container transportation mode choice. The results show that five parameters affect the modal shift towards intermodal rail: transport costs, transit time, delays, frequency of intermodal rail transport, and free time in the dry port.

According to the literature, researchers have paid attention to containerized dry and reefer cargo and supply chain analysis. As a complementary study to the literature, this chapter investigates the port and supply chain analysis for transporting containerized reefer and dry cargo on the maritime round trade route from West Africa to Europe. This research is novel in this concept as it considers the dry and reefer cargo from four African ports to three possible main hubs in West Europe. Also, it considers transshipments cargo from West Europe and non – transshipment reefer cargo from the Baltic region, the UK, and Northern part of the North Sea, and Ireland. Therefore, the results provide a general overview for many African and European ports and hinterland areas.

7.3. Methodology

In this section, first, the data collection approach and its results are explained, and then the updated CCM as the primary applied methodology of this chapter is described in detail.

7.3.1. Data collection

In the first stage, desk research is employed to gather the availability of cargo flows from the West-Africa to Europe (outbound leg) and Europe-West-Africa (return leg) trade route.
In the outbound leg, the dry and reefer cargo flows originating from the four West-African ports, namely Tema (Ghana), Douala (Cameroon), Abidjan (Ivory Coast), and Dakar (Senegal), to Europe are taken into account.

However, in the return leg, the dry and reefer cargo flows departing from the major European container ports (non-transshipment cargo – see Table 7.3) to West-African ports are considered.

Also, in this leg, the additional and potentially reefer cargo flows (transshipment cargo) originating from three regions, namely the Baltic region, Kattegat region, and Ireland, can be transhipped via either the ports of Rotterdam, Flushing, and Antwerp to the four West-African ports are considered. For both legs, the data of dry and reefer cargo flows are selected at the port level.

Table 7. 3: Major EU and UK ports in the loop

	Considered ports
EU ports	Antwerp, Rotterdam, Flushing, Zeebrugge, Le Havre, Brest, Montoir de Bretagne, Vigo, Marin, Lisbon, Sines
UK ports	London Gateway, Liverpool, Portsmouth, and Felixstowe

7.3.1.1. Data Collection for Outbound leg

The dry and reefer container cargo flows from four main West-African ports to the EU are obtained by a third-party company specializing in producing, transporting, and distributing fruit and vegetables.

7.3.1.2. Data Collection for Return leg

As mentioned, the container cargo flows for the return leg are divided into two types: (i) non-transshipment cargo and (ii) transshipment cargo. Furthermore, at this stage, the container cargo flows (both transshipment and non-transshipment) must be split up into (iii) reefer and (iv) dry cargo flows. This section describes the data collection sources and division ratio process for these types of cargo.

Non-transshipment cargo

The container cargo flows originating from the major EU and UK ports are obtained from Dynamar B.V. This dataset provides the total transshipment and non-transshipment cargo, including dry and reefer containers.
The transhipment ratios for the major ports are based on Portopia[33], which highlights the transshipment shares of major container ports. By applying the transshipment ratios to the dataset from Dynamar B.V., an estimation for the share of transhipped and non-transhipped TEUs on the return leg (Europe-West-Africa) is achieved. However, a value of 35% is assumed for ports where transshipment ratios are not provided.

Besides, to acquire the ratio of reefer and dry container cargo flows, the container throughput statistics for the port of Las Palmas are applied. The data considers the port of origin and port of destination pairs for all cargo transhipped at the port of Las Palmas and categorizes them by cargo type. By using these ratios for the relevant origin-destination pairs on the dataset of Dynamar B.V., the ratio among dry and reefer containers that are directly shipped (non-transshipment) from the major European ports to West Africa are evaluated.

The non-transshipment (detailed) cargo volume is separately split into dry and reefer cargo. For each type of cargo, the non-transshipment volume (in TEU) for 2018 is collected for all the major European ports in this study. The market share for dry cargo is 10%, while the reefer cargo market share is 50%. Moreover, the maximum cargo capacity of the vessel is 1,200 TEUs for reefer containers, while the cargo capacity of the ship for dry containers is 600 TEUs.

Computation of non-transshipment dry cargo volume weekly:

I. *The total number of containers per year (TEU) for each European port is multiplied by the estimated potential market share for dry cargo (10%).*
II. *The obtained value is divided by the number of weeks per year (52) to get the number of containers per week.*
III. *As the total capacity of the vessel* [34] *for dry containers is 600 TEU, the obtained values in step 2 are divided by 600 TEU to obtain the weekly percentage of loading dry cargo share in each European port returning to African ports.*

Computation of non-transshipment *reefer* cargo volume weekly:

I. *Each European port's total number of containers per year (TEU) is multiplied by the estimated potential market share (50%).*
II. *The obtained value is divided by the number of weeks per year (52) to get the number of containers per week.*
III. *To obtain the weekly percentage of loading reefer cargo share in each European port going back to African ports, the obtained values in step 2 are divided by 1,200 TEU (total capacity of the vessel for reefer containers is 1,200 TEU).*

[33] PORTOPIA – 7th Framework Programme (2014). Towards a competitive and resource efficient port transport system

[34] The vessel size is 2,339 TEU. More details of the characteristics of the vessel will be discussed later.

Based on the collected data, Antwerp, Le Havre, Montoir de Bretagne, and London Gateway have the highest cargo loading share in the (southbound going back) return leg to all four African ports; therefore, these ports are taken into account for the cost calculation. Table 7.4 plots the loading cargo share of non-transshipment volume for each of the above-mentioned European ports.

Table 7. 4: Loading cargo percentage based on the dry and reefer market share

Calling at port	Total loading %	Loading dry share %	Loading reefer share %
London Gateway	5%	4%	1%
Antwerp	54%	14%	40%
Le Havre	22%	5.5%	16.5%
Montoir	3%	1%	2%
Total	84%	24.5%	59.5%

In the ports of Antwerp and Le Havre, the reefer cargo share is approximately three times that of the dry cargo share, while in the port of London Gateway, the dry cargo share is higher than the reefer cargo share.

Transshipment cargo

As mentioned, three regions are considered the extra possible origins of cargo flows that can be transhipped via the ports of Rotterdam, Flushing, and Antwerp for the return leg. These regions are as follows:

- Baltic region: Poland, Finland, Sweden, Estonia, Russia, Latvia, and Lithuania
- Kattegat region: Denmark and Norway
- Ireland

The UN Comtrade database[35] is consulted to collect the cargo flows from these three regions to the West-African regions.

The transshipment (aggregated) cargo volume is based on the reefer type of cargo. Therefore, the transshipment (aggregated) cargo flow originating from the Baltic, Ireland, and Kattegat regions and Russia, transshipped via the port of Antwerp to all African ports, is taken into the calculation.

In this case, for the Baltic, Ireland, and Kattegat regions, a market share of 50% is remarked, while for the transshipment cargo from Russia, a potential market share of 25% is assumed. For both cases, the maximum cargo capacity for reefer cargo of the ship is considered 1,200 TEU. Then, The obtained value is divided by the total number of weeks per year (52) to obtain the number of containers per week. Consequently, to get the weekly percentage of loading transshipment reefer cargo share in each region going back to African ports, the obtained values in the previous step are divided by 1,200 TEU (total capacity for reefer containers)—tables 7.5 and 7.6 plot the loading and unloading cargo share.

Table 7. 5: Loading cargo share in each transshipment cargo region

From Baltic-Ireland-Kattegat-Russia to four African ports	Number of containers [TEU/year]	Market share	Number of containers [TEU/year] with market share	Number of containers [TEU/week]	Loading cargo in each region per week
Baltic	3,663	50%	1,832	35	3%
Ireland	7,470	50%	3,735	72	6%
Kattegat	3,365	50%	1,683	32	2.7%
Russia	5,863	25%	1,466	28	2.3%
Total	**20,361**		**8,715**	**168**	**14%**

Table 7. 6: Unloading cargo share in each African port from transshipment cargo regions

From Baltic-Ireland-Kattegat-Russia to four African ports	Number of containers [TEU/year]	Number of containers [TEU/year] with market share	Number of containers [TEU/week]	Unloading cargo in each African port per week
Dakar	1,111	553	11	1%
Tema	4,690	2,319	45	4%

[35] The UN Comtrade database is detailed in the different types of products that are shipped between different regions and lists down traded commodity volumes (in kilograms) by origin and destination, by period, and under respective trade flows (import/export).

Douala	10,717	4,295	83	7%
Abidjan	3,843	1,549	30	2%
Total	**20,361**	**8,715**	**168**	**14%**

Based on the results, the total transshipment cargo volume share originating from the Baltic, Ireland, Kattegat, and Russia that can be transshipped to all African ports is 14%. Among all African ports, the port of Douala is the most desired as half of the transshipment cargo share (7%) is transported to this port.

7.3.2. Updated version of CCM

A detailed explanation of the CCM was provided in chapter 3, and the updated model with functionality to estimate the vessel owner cost was explained in chapter 5. In this chapter, this updated model is used; however, based on the objectives of this study, a new maritime route and four new ports with their input parameters and data are incorporated into the model [36]. To apply CCM for this chapter, the updated version includes defining a new maritime route called Africa-Europe to the model as the focus of the study is the trade route between West Africa and Europe. Furthermore, four main African ports, namely Abidjan, Douala, Tema, and Dakar, are added to the model along with the existing terminal of each port. Next, the model is updated with adjusting all the necessary input data[37] such as infrastructure and the types of equipment of terminals, container handling rates, port dues, pilotage, rate of cargo loading, and unloading in the terminal, etc. of the four African ports and their specified terminals in the loop.

Figure 7. 1: Four African ports

Table 7. 7: Terminals of four African ports

Port in West Africa	Abidjan	Douala	Tema	Dakar
The terminal in each port	APMT Bollore Terminal	Douala International Terminal	Terminal 1 and 2	Terminaux Vraquiers du Senegal

Other details such as vessel size, fuel used inside and outside ECA, etc., are reported in Table 7.8.

Table 7. 8: Features of the vessel

Property	Value	Property	Value
Vessel size (TEU)	2,339	Fuel used In ECA	MDO
Installed power (kW)	12,832	Fuel used Out ECA	HFO

[36] Read chapter 3 for further info regarding CCM.
[37] The data is obtained from the port websites of the different ports.

Design speed (knots)	19.1	Fuel used of main engine (tons/hour)	4.58
Payload ship	It is calculated based on actual data of loading in the port	Type of engine	Diesel Engine

In the calculation process, for the internalization of external costs, the external costs of pollutants such as SO_x, NO_x, CO_2, and PM are addressed in the model. Table 7.9 reports the external costs of pollutants.

Table 7. 9: External costs of pollutants

Type of cost	Value (EUR/Ton)
Cost SO_x	0.04
Cost NO_x	1,328
Cost PM10	0.48
Cost CO_2	25

Source: van Essen et al. 2011

However, in this study, the maritime and hinterland costs of transporting the potential cargo from the Baltic, Ireland Kattegat, and Russia to the port of Antwerp are not taken into calculation due to lack of data availability.

7.4. Calculation process and scenario development

This section explains each scenario in detail, together with the order of ports of call in each scenario. Based on the obtained data and the share of loading and unloading cargo in each port, the calculation has been performed, and the results have been provided.

7.4.1. Scenario development

To fulfill the objectives of this study, five different transport chains (defined from a production location in Africa to a warehouse in Europe) are included in the analysis. These transport chains are (i) West-African origin to Lille (France), (ii) West-African origin to Rennes (France), (iii) West-African origin to Chateaurenard (France), (iv) West-African origin to Gyal (Hungary), and (v) West-African origin to IJselmuiden (Netherlands).

These chains are selected as these European destinations play an essential role in the dry and reefer cargo in West Africa – EU trade route based on the consultancy with the classified company specializing in producing, transporting, and distributing fruit and vegetables. Moreover, three European countries are diverse in terms of geographical location, namely France (Western Europe), The Netherlands (Northwestern Europe), and Hungary (Central Europe). They are selected first to have a comparative analysis in Western-European countries (between The Netherlands and France) and second to have a competitive overview of a Central-European region with conventional Africa to West-Europe trade route.

There are three candidate ports in West-Europe, namely ports of Antwerp, Rotterdam, and Flushing, among which, among them, only one port needs to be considered the central hub for the return leg.

7.4.2. Pre-scenario and the best port selection:

To figure out which port shows the best results in terms of the lowest vessel owner cost and also the lowest generalized chain cost, three pre-scenarios are taken into consideration in which in pre-scenario A (un)loading cargo share of the only port of Antwerp is selected, while in pre-scenarios B and C (un)loading cargo share of ports of Rotterdam and Flushing are considered respectively. Furthermore, for all these three pre-scenarios, London Gateway has been assumed in the calculations as this port is a popular destination for the outbound leg.
In the calculation process, it is assumed that in the outbound leg, the unloading share is 20% for London Gateway and 80% for the port of Antwerp. However, in the return leg, the loading share is based on the obtained data of both dry and reefer cargo types of the non-transshipment cargo volume originating from ports of Antwerp (pre-scenario A), Rotterdam (pre-scenario B), and Flushing (pre-scenario C) are taken into computation separately. The following figures display the (un)loading percentage share for the three pre-scenarios.

Figure 7. 2: Ports of call and loading and unloading cargo share in pre-scenario – Route A (Antwerp)

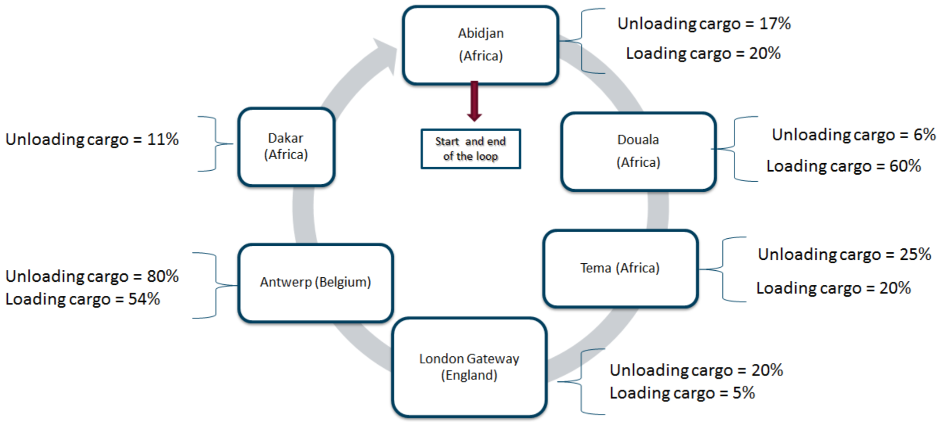
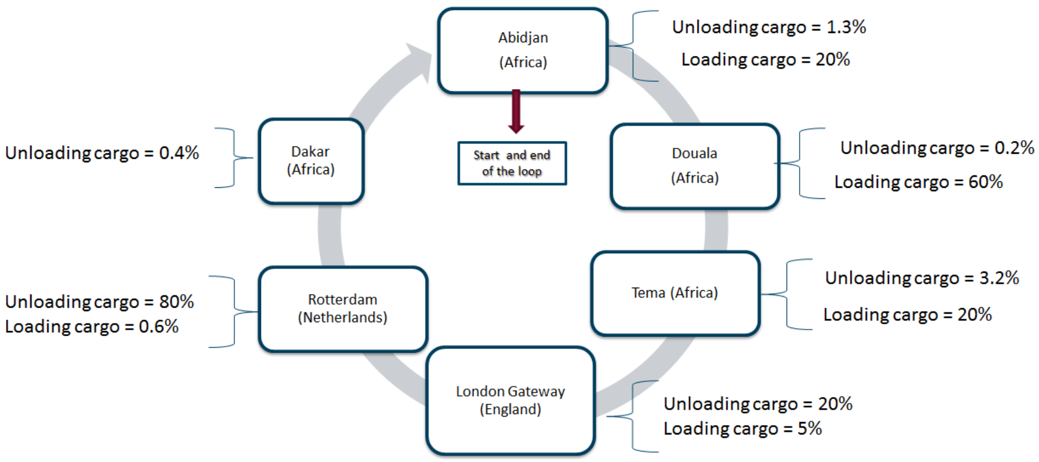
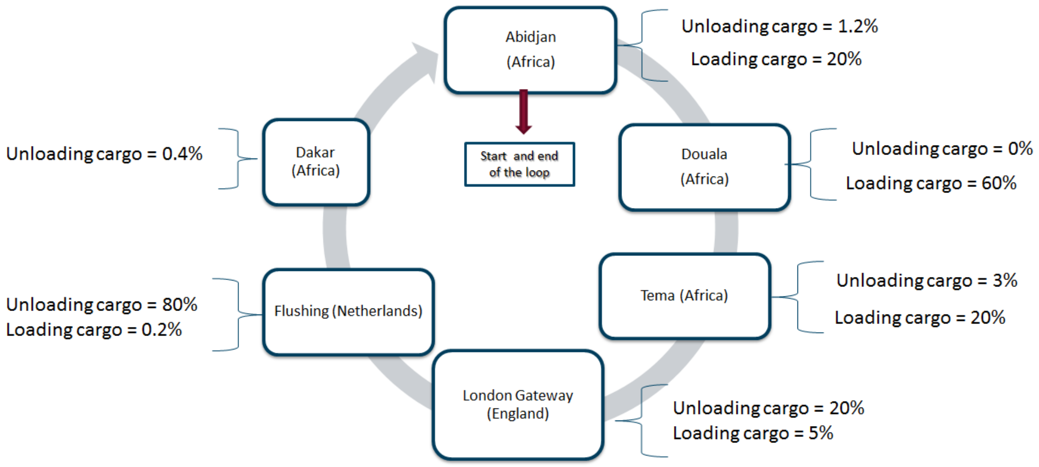


Figure 7. 3: Loading and unloading cargo share in pre-scenario – Route B (Rotterdam)



The port of Rotterdam has only an 0.6% share of cargo loading, while the port of London Gateway has a 5% cargo loading share.

Figure 7. 4: Loading and unloading cargo share in pre-scenario – Route C (Flushing)



By comparing the loading cargo share at Antwerp, Rotterdam, and Flushing, it is observed that the port of Antwerp has the highest share (54% of cargo loading) compared to the other ports.

By running the CCM, the total cost of vessel per loop and the generalized chain cost are computed for the three pre-scenarios and plotted in the following Figures.

Figure 7. 5: Vessel owner cost – pre-scenarios A, B, C

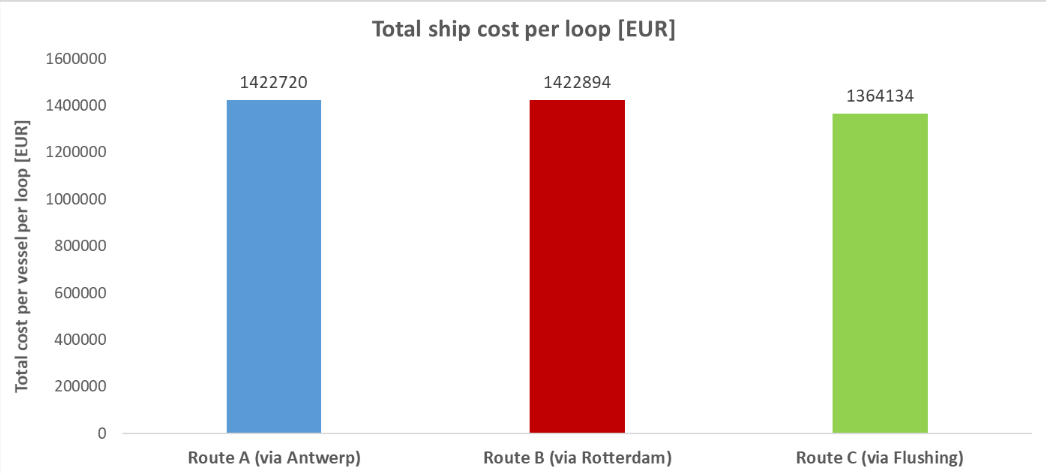
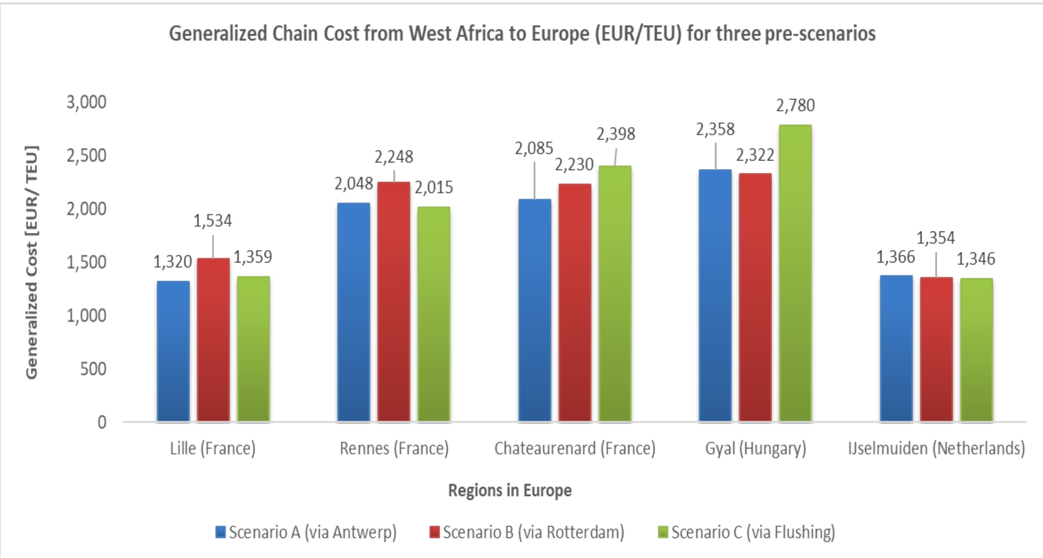


Figure 7. 6: Generalized chain cost – pre-scenarios A, B, C



Based on the results, the port of Antwerp is considered the best option compared to Rotterdam and Flushing for two main reasons. Firstly, by comparing the total cost of the ship in each loop, the port of Antwerp is a bit more expensive than Flushing; however, this issue is justified by considering that the port of Antwerp has a much higher loading cargo share (54%) compared to the other two ports (0.6% in Rotterdam and 0.2% in Flushing).

Secondly, by comparing the results of the generalized chain cost, it is observed that the chain cost is altering in each region, and the port with the lowest generalized cost varies. The port of Antwerp has the lowest generalized chain cost for the routes from Africa to two regions in Europe, namely Lille

(France) and Chateaurenard (France). However, the port of Rotterdam shows the most expensive generalized chain cost for the route from Africa to Rennes (France).

Similarly, the most expensive generalized chain cost for the route from Africa to Chateaurenard (France) and Gyal (Hungary) is obtained via the port of Flushing. In conclusion, given the fact that the port of Antwerp has a much higher loading cargo share (54%) compared to the other two ports, it can be concluded that the port of Antwerp shows better results and is selected as the best option.

7.4.3. Scenario development and obtained results

In this study, two main scenarios are considered for the calculation process. Scenario 1 discusses the non-transshipment (detailed) cargo flow originating from the major European ports going back to four African ports, namely Dakar, Tema, Douala, and Abidjan.

Scenario 2 considers non-transshipment (detailed) cargoes from the major European ports and transshipment (aggregated) container flows originating from Baltic, Ireland, and Kattegat regions and Russia transported via the port of Antwerp to all four African ports.

For each scenario, the maritime loop starts and ends with the port of Abidjan. In addition, based on the obtained data from the classified company, in the outbound leg (West-Africa-Europe), the loading cargo share in the port of Abidjan is 20% of the total capacity of the ship, while this share in the port of Douala is 60%, and in the port of Tema, it is 20% respectively. Nonetheless, in the return leg (Europe-West-Africa), the unloading cargo share in all African ports is computed precisely based on the actual handling cargo originating in the European ports.

7.4.3.1. Scenario 1

In this scenario, non-transshipment cargo flows originating from London Gateway, Antwerp, Le Havre, and Montoir de Bretagne (these ports have the highest potential volumes for the return leg), going back to all four African ports are taken into consideration. The following Figure presents the order of calls in the loop and (un)loading cargo share at each port.

Figure 7. 7: Order of ports and (un)loading share (dry and reefer cargo) – scenario 1

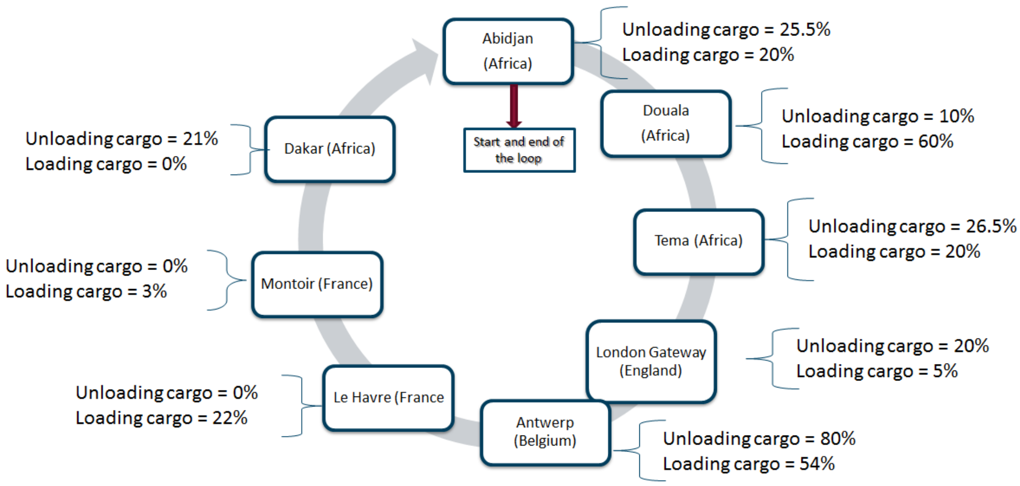


Table 7. 10 and Table 7. 11 describe the breakdown of (un)loading share of cargo at each port based on dry and reefer cargo market share.

Table 7. 10: Loading cargo % at European ports based on the dry and reefer market share – scenario 1

Calling at port	Total loading %	Loading dry share %	Loading reefer share %
London Gateway	5%	4%	1%
Antwerp	54%	14%	40%
Le Havre	22%	5.5%	16.5%
Montoir	3%	1%	2%
Total	**84**%	**24.5**%	**59.5**%

In scenario 1, the ship is loaded with 84% of the ship's total capacity, of which 24.5% is the dry cargo and 59.5% is reefer cargo.

Table 7. 11: Unloading cargo % at African ports based on the dry and reefer market share – scenario 1

Calling at port	Total unloading %	Unloading dry share %	Unloading reefer share %
Dakar	21%	6%	15%
Tema	26.5%	8.5%	18%
Douala	10%	3%	7%
Abidjan	25.5%	7%	18.5%
Total	**84**%	**24.5**%	**59.5**%

Obtained results of scenario 1

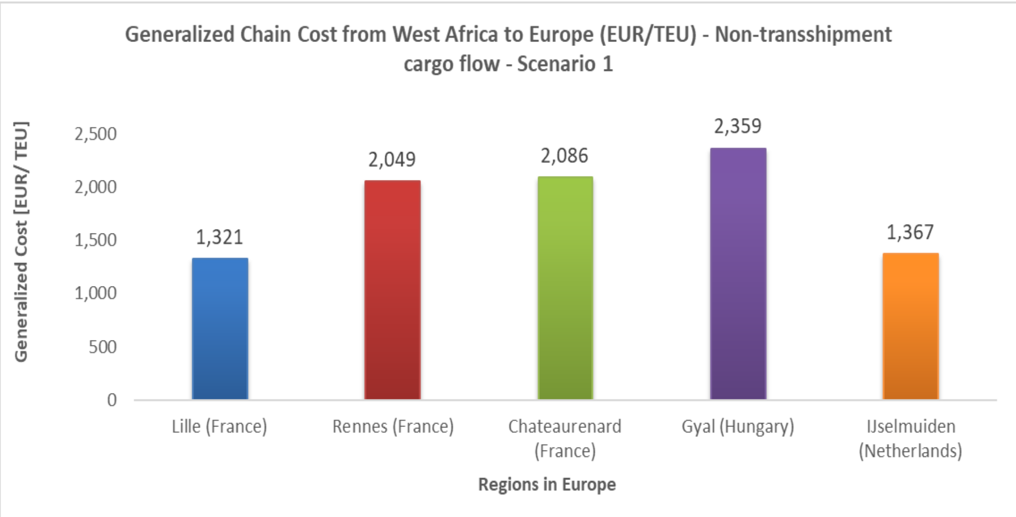
The total cost per loop (vessel owner cost), the number of vessels required, and the generalized chain cost are calculated by running the CCM. The results of the vessel owner cost and the required number of vessels are plotted in Table 7. 12. As can be seen, five vessels are required to keep the weekly departure from the origin.

Table 7. 12: Vessel owner cost and required vessels in scenario 1

Scenario 1	Type of cargo	The total cost of the ship per loop [EUR]	Number of vessels
	Non-transshipment cargo (both dry and reefer)	1,529,538	5

The generalized chain cost from Africa to all five European regions in scenario one is presented in the following Figure.

Figure 7. 8: Generalized chain cost for European regions in scenario 1

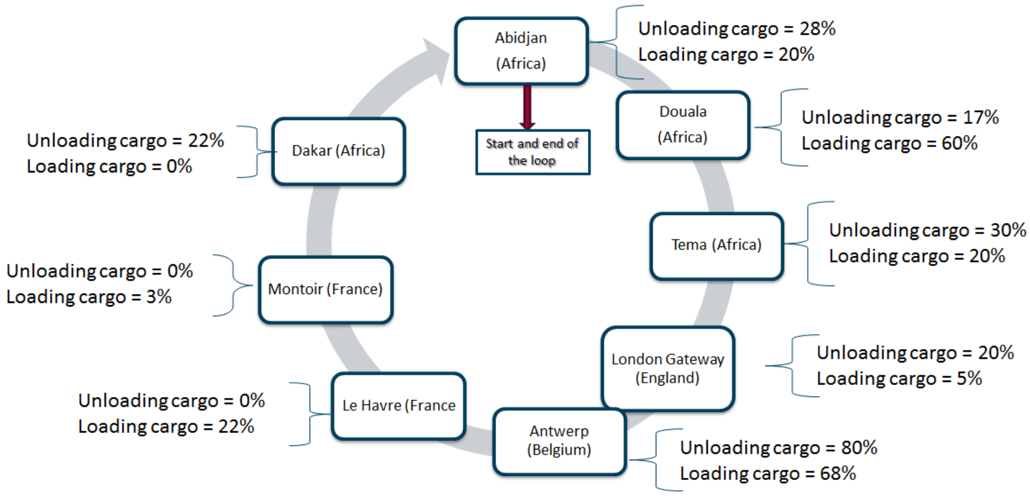


The generalized chain cost from Africa to region Gyal (Hungary) in Europe has the highest value. Chateaurenard (France) and Rennes (France) are the second and third most expensive regions in Europe, respectively, while the generalized cost from Africa to Lille (France) shows the lowest value. However, the generalized chain cost comparison between Lille (France) and IJselmuiden (the Netherlands) is not high, and these two regions show the same result approximately.

7.4.3.2. Scenario 2

In this scenario, non-transshipment cargo flow originating from ports of London Gateway, Antwerp, Le Havre, and Montoir de Bretagne (scenario 1), together with transshipment cargo flow originating from Baltic, Ireland, Kattegat, and Russia that are transshipped via the port of Antwerp, going back to all four African ports are taken into account. The order of calls in the loop and (un)loading cargo share at each port is plotted in Figure 7.9.

Figure 7. 9: Order of ports and (un)loading share (non-transshipment and transshipment cargo) – scenario 2



In this scenario, the ship is loaded with 98% of the ship's total capacity, of which 14% belongs to the transshipment cargo flow originating from the Baltic, Ireland Kattegat, and Russia transshipped via the port of Antwerp. Table 7. 13 and Table 7.14 plot the (un)loading share of cargo at each port.

Table 7. 13: Loading cargo % at European ports based on the dry and reefer market share – scenario 2

Calling at port	Total loading %	Loading dry share %	Loading reefer share %
London Gateway	5%	4%	1%
Antwerp	**68%**	14%	**54%**
Le Havre	22%	5.5%	16.5%
Montoir	3%	1%	2%
Total	98%	**24.5%**	**73.5%**

Table 7. 14: Unloading cargo % at African ports based on the dry and reefer market share – scenario 2

Calling at port	Total unloading %	Unloading dry share %	Unloading reefer share %
Dakar	22%	6%	16%
Tema	30%	8.5%	22%
Douala	17%	3%	14%
Abidjan	28%	7%	20.5%
Total	**98%**	**24.5%**	**73.5%**

Obtained results of scenario 2

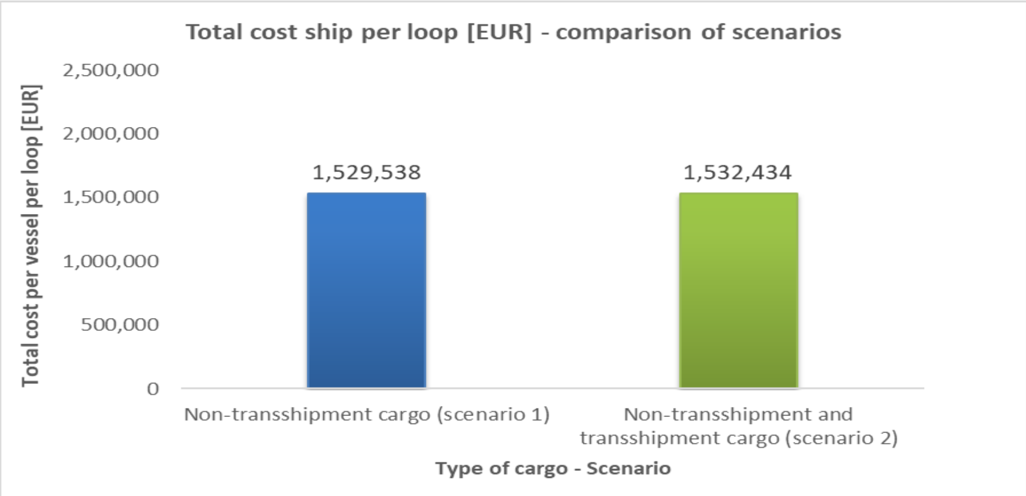
The CCM is applied to calculate the total cost of the ship, the required vessels, and the generalized cost in this scenario. First, the vessel owner cost and the required number of vessels are displayed in Table 7.15.

Table 7. 15: Vessel owner cost and required vessels in scenario 2

Scenario 2	Type of cargo	The total cost of the ship per loop [EUR]	Number of vessels
	Non-transshipment (dry + refeer cargo) and trasnsshipment (reefer cargo)	1,532,434	5

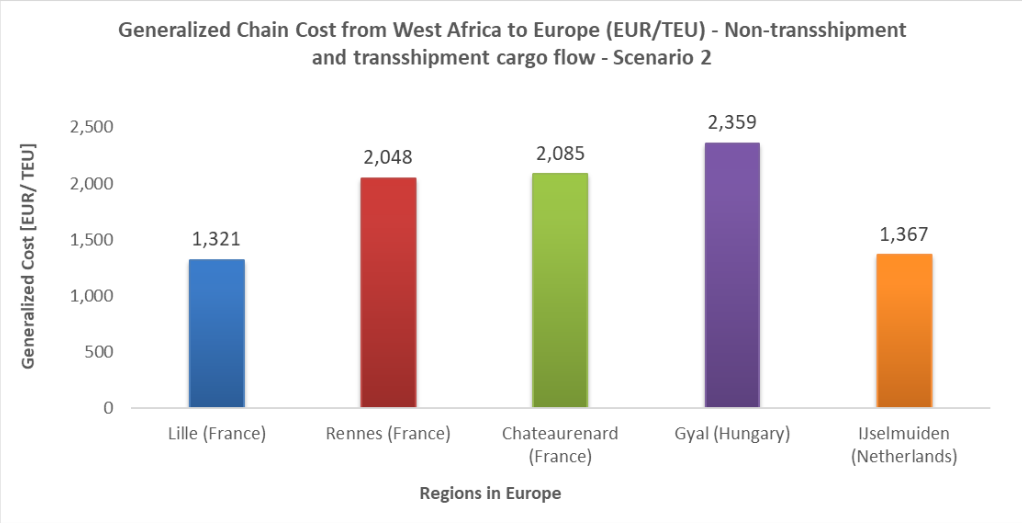
In this scenario, five vessels must keep the weekly departure from the origin.

Figure 7. 10: Comparison of total vessel cost of the ship in the first and second scenarios



By loading more cargo at the port of Antwerp due to the potential market in the Baltic, Ireland Kattegat, and Russia, the ship's total cost increases slightly as the port handling costs rise. Moreover, the generalized chain cost from Africa to all five European regions in scenario two is illustrated in Figure 7.11.

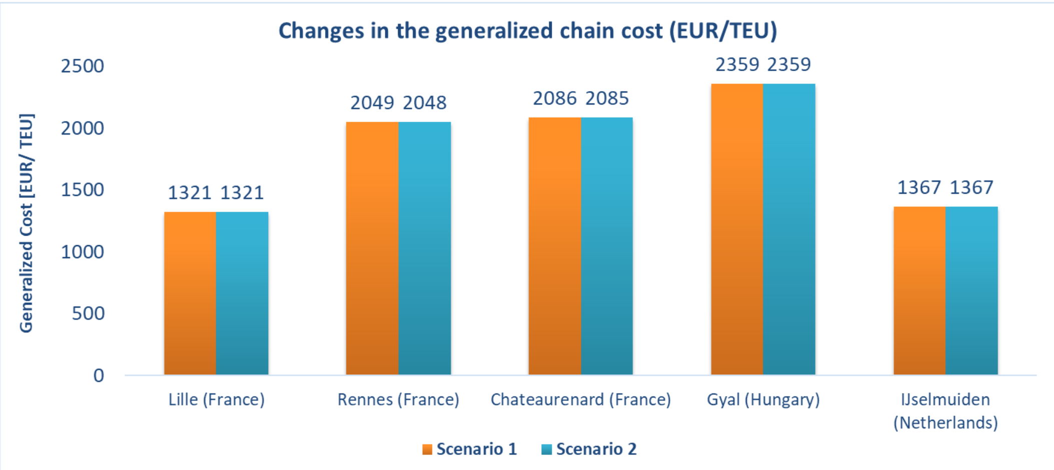
Figure 7. 11: Supply chain cost – scenario 2



Based on the results, the generalized chain cost from Africa to region Gyal (Hungary) in Europe has the highest value. Chateaurenard (France) and Rennes (France) are the second and third most expensive regions in Europe, while the generalized cost from Africa to Lille (France) shows the lowest value.

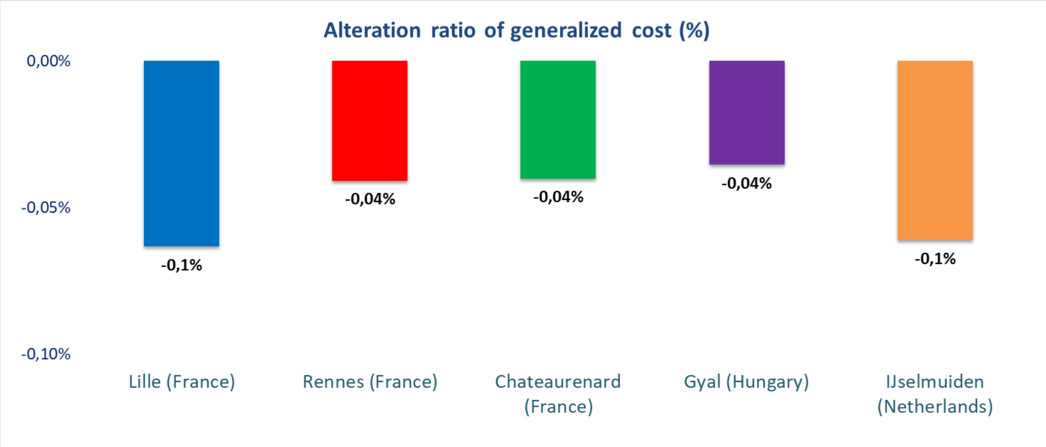
By comparing the generalized chain cost between the first and second scenario, it is observed that the lowest generalized chain cost from Africa to the European regions: Lille (France), Gyal (Hungary), and IJselmuiden (the Netherlands) does not differ, while for the regions Rennes (France) and Chateaurenard (France), the generalized chain cost in the second scenario reduces slightly but the difference is insignificant.

Figure 7. 12: Changes in supply chain costs between scenarios 1 and 2



Moreover, scenario two reduced the generalized chain cost by approximately -0.1% based on the obtained results.

Figure 7. 13: Percentage changes in supply chain costs between scenarios 1 and 2



7.5. Conclusion

Based on dry and reefer cargo types, this chapter sheds light on containerized cargo flow between the maritime loop between West Africa and Europe. Besides, other regions such as the UK, Baltic, the Northern part of the North Sea, and Ireland are considered. Next to the data collection approach to realize the potential of cargo flow in each region, the adjusted CCM is applied to appraise the ship's total and generalized costs.

Two research questions are examined: *(i) which of the three ports of Antwerp, Rotterdam, and Flushing might be the main port of call in North-West-Europe? and (ii) what the economic influence of calling at more ports (than the selected ports among Antwerp, Rotterdam, and Flushing) on the vessel owner and the supply chain costs of transporting cargo for the trade route West-Africa-Europe is?*

Concerning the first point, it can be concluded that the port of Antwerp is the best option compared to Rotterdam and Flushing for two main reasons. Firstly, the port of Antwerp has much more loading cargo potential (54%) than the other two ports (0.6% in Rotterdam and 0.2% in Flushing). Secondly, it is observed that the port of Antwerp has the lowest generalized chain cost for the routes from Africa to three regions in Europe (all regions in France).

The difference with the port of Rotterdam and Flushing for the other two regions (IJselmuiden and Gyal) is minimal (<1%). Also, the vessel owner's cost for calling at the port of Antwerp is almost the same as when the port of Rotterdam is called at. Concerning the port of Flushing, it can be concluded that the total vessel owner cost is a little bit lower compared to the port of Antwerp (-4%). Given the fact that the port of Antwerp has much more loading cargo (54%) compared to the other two ports, it can be concluded that the port of Antwerp shows the better result and is selected as the best option.

Therefore, Antwerp is the most attractive port to use as the central hub in Northwest Europe. Moreover, the most attractive port to call is London Gateway from the UK ports because this port has the possible cargoes for the backhaul load. The linkages with the ports of Tema and Abidjan are the strongest. In terms of the second argument, it may be concluded that the maritime loop can be extended to include both Le Havre and Montoir de Bretagne ports.

Based on the obtained results, it is determined that Antwerp and Le Havre ports have the most significant potential cargo flows for the backhaul. The ports of Montoir de Bretagne and Rotterdam have some possible quantities, but they are far lower.

There is a significant possibility of reefer containers in Antwerp and Le Havre. These ports can also load many dry containers, allowing the vessel to be loaded with non-reefer containers.

From a cost viewpoint, it is inferred that calling at the ports of Le Havre and Montoir de Bretagne (scenario 1) will raise the overall vessel cost by 8% compared to not calling at the ports (pre-scenario).

By analyzing the four African ports, it is observed that Tema and Abidjan can handle the majority of the backhaul cargo. The volume of traffic to Dakar and Doula is lower. However, because Doula is called at anyway, this cargo could still be attractive to load in the backhaul, and the volumes at the port of Dakar are still large enough to consider a call there. In conclusion, the potential volume coming from the UK ports is much less than the EU ports. The Baltic region has enormous potential volume in terms of possible reefer cargo transshipment volumes. There is much possible cargo that might be shipped to West Africa from Ireland.

Chapter 8: Conclusion

Maritime shipping has encountered many challenges in sustainability issues, including mitigating environmental emissions such as reducing air pollution, avoiding the spread of invasive species by ballast water, increasing profitability, and enhancing social welfare. Meanwhile, the maritime industry has adopted green strategies to improve resource efficiency and competitiveness.

This Ph.D. sheds some light on filling some of the existing gaps in the literature and addressing two significant environmental implications caused by maritime shipping: air pollution and BW treatment, which aims at improving the sustainability of MarSC in all three aspects (economic, environmental and social) by employing numerous application studies.

The primary goal of this Ph.D. is to present a feasibility study of the most promising technologies and approaches for mitigating the adverse effects of the maritime shipping and port industries not only from air pollution of SO_x and NO_x but also from other environmental legislations perspectives such as BWM Convention and local and national communities for security at the ports. All the aspects of MarSC sustainability are covered in which the critical sustainability dimension studied in all chapters is maritime economics, and environmental regulations and social concerns are the driving forces of this Ph.D.

The overall addressed research question of this Ph.D. is:

What is the economic impact of sustainability issues on maritime shipping in various trade routes from different stakeholders' standpoints?

As an initial step to answering the critical research inquiry, 262 papers from 2000 to 2020 are meticulously assessed. According to the literature, most studies on the topic of MarSC are connected with environmental sustainability and emission reduction, whereas studies on the economic and social aspects of MarSC are sparse.

Furthermore, academia and industry have focused on the sustainability of the MarSC, and different studies have been conducted on this concept. However, the analytical findings support the view that the effects of green policies and emission restrictions on shippers have attracted scant attention.

Next, different methodologies are applied to respond to the main research question in which CCM is the primary tool. CCM is updated with the newest input data of vessel sizes, port, and terminal equipment and costs, adjusted cost components, and new maritime routes in each relevant chapter. Besides, chapter 4 applies a new typology of potential vessel types in the SRA and cost-benefit evaluation to achieve the objectives. Chapter 6 establishes a novel scanning cost approach by considering various cost factors and multiple stakeholders' viewpoints.

The following sections, firstly, elaborate on the applied methodologies and the overall results and findings of each application study by answering the overarching research question of the dissertation. Also, it describes the acquired knowledge of the outcomes in a global context. Subsequently, the implications of results on different stakeholders such as industry partners and academia are illustrated. Finally, the limitations of the thesis are discussed, with some suggestions and directions for further research.

8.1. Economic impact of SRA under the BWMC

The BWM and its exemptions have been analyzed extensively from an ecological standpoint, and little research has been performed from an economic point of view. Moreover, the ecological and economic incentives for constructing an SRA are two different issues. However, the goal of this research is not to examine the economic-environmental conflict. Still, the goal is to establish a method for calculating an SRA's economic viability in the North Sea between the Netherlands and Belgium with the possibility to apply it worldwide by assuming that all environmental standards are satisfied.
Thus, in chapter four, an economic repercussion of a prospective SRA in (regions of) the Netherlands and Belgium is assessed, in which it examines the economic effects of a BWM in SRA from the standpoint of vessel owners by assuming that ecological risk is approved based on the BWM guidelines of risk assessment. A novel typology is developed to classify the vessel types navigating with the SRA ports exempt from BW treatment. Next, the cost-benefit estimation of the selected vessel sizes is fulfilled.

A new typology of vessel types in the SRA was established based on yearly BW consumption and previous port call of vessels. The typology classifies the ships as small vessels (navigating completely) and others (sailing partially) in the SRA. The decisive factor to recognize if a vessel is profitable to use SRA is the yearly BW consumption which should not exceed 70,000 tons/year. Then, a cost-benefit analysis was used for the ships based on the typology gained, which results in the total net benefit of installing the SRA. Furthermore, desk research and data collecting from the authorities of the ports covered in the study are the approaches used to obtain data.

8.1.1. Response to the overarching research question

The research raises some significant points to answer the overarching research question. Based on the results of the SRA's cost and benefit estimations, it can be concluded that the economic effects of having such SRA are not profitable for vessel owners. The first reason is that ecological risk should be assessed carefully to comply with regulations, which comes at a cost.
Secondly, the total benefit for vessels only navigating in the SRA is insignificant, given the fact that these vessels carry a small amount of BW and their relative share of the total number of ships calling at the various ports is small. Moreover, for the vessels sailing partially in the SRA (the vessels navigating within SRA ports), although the results show that total benefits for all types of ships calling at the Dutch SRA ports (Rotterdam and Zeeland seaports) are higher than for all the vessel types calling at the Belgian ports (Antwerp, Zeebrugge, and Ostend), the yearly BW consumption of these vessels should not exceed 70,000 tons. However, by increasing the amount of yearly BW consumption or in case of sailing to other external ports outside the SRA, the vessels should be equipped with their own BW treatment system; hence, an onboard installation is inevitable for vessel owners to treat BW.

In addition, it might be the case that the costs of onboard BWTS will be reduced due to technological progress; therefore, the maximum value which allows applying a shore-based system (70,000 tons/year) will be less. Consequently, it will decrease the number of vessels using shore-based techniques to treat BW. Also, due to possible technical problems at the ports providing shore-based systems, vessel owners need to install an onboard BW treatment system to avoid congestion at ports and smoothen the supply chain. These issues would lead to a decrease in the number of vessels using a shore-based system and confirm that even with establishing an SRA within some neighboring ports, it remains necessary for vessel owners to install an onboard system to treat the discharged BW.

The same concept applies to other ports worldwide such as Malmo – Copenhagen ports and Trieste – Koper ports. Based on the insights obtained from the performed study for Antwerp and Rotterdam, it can be concluded that the SRA exemption can only be used for a few vessel types, namely service and special purpose vessels which only sail in the same region, the benefit of saved cost of BW exemption is not that high to compensate the SRA costs. Thus, regardless of the overall net advantage of establishing an SRA, a BW treatment system must be installed onboard.

8.2. Economic evaluation of alternative technologies to mitigate sulfur emissions

It is observed that several green initiatives such as slow steaming, scrubber systems, alternative fuels, namely MDO, LNG, Ammonia, Hydrogen, and Methanol, aiming at mitigating GHG and maritime air pollution, have been assessed economically and environmentally in the literature. In addition, the effectiveness of international regulations by IMO on reducing the environmental effects of marine shipping in ECA's is a significant concern in the industry.
In this research, as the significance of the reduction of ship emissions in ECAs has been emphasized, which necessitates ship owners and shipping lines to respect the regulations, the primary purpose was to determine which of all the available options in compliance with the ECAs regulations is economically most suitable for the vessel owners and the cargo owners.

The CCM is the starting point for the investigation. The model was further improved and modified to answer the specific research problems addressed in this chapter. It was also enhanced to calculate the vessel owner's cost by computing the whole expenses of operating a container ship in a loop.

8.2.1. Response to the overarching research question

The developed study in chapter five had two research objectives. First, the evaluation of the cost for the vessel owner, and second, the assessment of chain cost of some types of containerships trading between Europe, the US, and Far East Asia based on three alternative fuel options, LNG, MDO, and scrubber technology from the cargo owner standpoint.
In response to the main research question, the LNG system would be the most cost-effective alternative technology for both maritime routes since it offers the most significant cost reductions compared to other scenarios. Besides, the cost savings of the scrubber scenario are negative for all the vessels, which means that it is a more expensive option than LNG fuel. This trend is correct for both vessel owners and shippers, as LNG positively affects maritime and generalized costs compared to the scrubber system.

It is worth mentioning that the cost of fuel has an immense impact on the overall cost. In this study, the fuel price of HFO is 400 EUR/ton and 310 EUR/ton for LNG. Therefore, cheaper fuel prices would result in the lowest maritime cost. For example, by changing the fuel price (increasing the LNG prices and reducing MDO), the LNG scenario becomes a less economical option but still has the highest cost savings compared to the scrubber system and is considered the most economical fuel alternative.

It is concluded that if the LNG price becomes more expensive, the potential to use it as an alternative fuel drops considerably. It applies to other fuels such as HFO as well. For instance, any dramatic increase in fuel price would result in a market change to another alternative fuel with a lower price; however, environmental impacts and technical and safety issues should not be overlooked.

This fact reveals that fuel price plays an essential role in choosing an alternative fuel option. Other significant factors are installation, crew, maintenance, and operational costs. As the cost of LNG rises, the overall cost ascends as well, reducing the cost savings of LNG compared to the base fuel price situation. However, the findings contrast with the number of ships using scrubber and LNG fueled ships. Roughly 4,000 vessels are equipped with a scrubber system, while around 200 LNG-fueled vessels operate. It can be justified that firstly, the retrofitting cost of LNG is higher than of scrubber system installation; also, the engine type of a ship with LNG is a dual one as conventional engines are incompatible with LNG. Next, the limited bunkering infrastructure of LNG is a significant concern for vessel owners, along with some safety concerns such as methane slip. In addition, the uncertainty of LNG fuel price remains an important issue for selecting LNG as an alternative fuel.

Therefore, given that there are more alternative fuels/technologies than LNG, it can be concluded that several factors and issues need to be considered to opt for alternative maritime fuel. These issues can be categorized into economic profitability, environmental regulations, social concerns, technical advancements, and political decisions.

Thus, the main decisive factors are fuel price, environmental legislation compliance, infrastructure facilities, safety issues, and compatibility with existing engines. Moreover, by considering all these issues, it is revealed that selecting a transitional alternative fuel is a multi-dimensional decision-making process and needs the collaboration of public and private stakeholders, namely port authorities, ship owners, energy providers, fuel suppliers, etc.

8.3. The feasibility of enhancing the supervision of maritime container supply chain from an economic perspective

With the increase in global threats, the customs authorities play a crucial role in ensuring external border and supply chain security, thus contributing to the overall security. Given the geopolitical security concerns, the importance of the detection technologies and associated tools concerning ensuring external border and supply chain security has taken on a new meaning. Detection technologies have long since played an essential role in customs border controls by detecting dutiable, prohibited, and controlled goods and materials.
The volume of international trade is increasing significantly, as is the emphasis on supply security and trade facilitation, thus leading to rapid developments in the role of customs authorities. For instance, data analysis has attained importance equal to detection technologies in addressing existing and emerging threats. Non-intrusive and innovative technologies or control equipment are needed to inspect high-risk cargo quickly without disrupting the flow of legitimate trade.

Chapter six investigated the possibility of security enhancement at the port of Antwerp through improved cargo supervision, which aims to reduce illicit trafficking and leads to improvement in the MarSC's economic and social aspects.

8.3.1. Response to the overarching research question

For the objective of this research, the novel scanning cost approach was developed to provide an economic assessment of maximizing the scanning rate. The reason is that the current scanning procedure and technology are not sufficient nor effective to satisfy the needs of customs to have complete control over the import containerized cargo at the port of Antwerp. Therefore, the model provides the economic consequences of different scanning rates and locations by considering the application time and supply chain impacts. The supply chain cost assessment is the second stage, and it evaluates the generalized chain cost from some Asian, Middle Eastern, and South American origin ports to the port of Antwerp for all five developed scenarios.
The outcomes allow concluding that in terms of both economic and supply chain implications, scenario five (a combination of 100% headspace sampling and ion trapping, 10% scanning at the gate out) has the lowest cost increment compared to the current situation. The use of AI for image analysis would reduce the number of image analysts involved, lowering scanning expenses associated with human image processing by around 9% on average. At the same time, in terms of supply chain effects, the cost decrease is substantially smaller and almost zero.

Based on the results from scenario five, all the import containers need to be tested via air analysis techniques, and a fraction of them must be scanned. In this study, this value is assumed to be 10%. However, the exact value for each terminal would differ. Some factors such as annual cargo turnover, terminal congestion, the possibility of scanning at different locations, the significance of illicit trafficking at the port, port competitiveness, etc., should be considered. This issue needs to be investigated in the further study of the research.

The obtained results confirm that the best scanning location for the imported containerized cargo would be inside the terminal and as close as possible to the unloading process. It can reduce the scanning cost and time and simultaneously avoid delays in the supply chain process and congestion at the terminal. By applying the scanning process somewhere outside the terminal, there is the risk of manipulating the contents of containers or disobeying the scanning process. Notably, regional and national risk assessment procedures and the communication process approach should be declared before scanning.

It is worth mentioning that AI is necessary but insufficient to perform the scanning model at a high scanning rate. Although it proved the immense reduction of analysts and image analysis time resulting in a considerable cost reduction, AI should be merged with state-of-the-art technologies and scanning devices to be effective and reach the maximum scanning rate. Furthermore, maximizing the scanning rate at the port causes a significant amount of investment and administrative and executive costs for port authorities and customs. Moreover, it affects the supply chain process by prolonging the terminal's operational time of handling cargo. These significant issues make the destination port unattractive, resulting in losing competition compared to neighboring ports in the region. As the shippers and shipping companies favor the port with higher efficiency and performance, they will eventually switch their final destination to another port with less congestion, a better cargo port service chain, and a higher terminal handling rate.

Therefore, this thesis suggests that the best option to increase the ports' security is to provide an international framework for all neighboring ports (here for all European ports) to comply with the same scanning operation for all the imported containers. In this case, all the ports would maintain the same competitiveness rate, and it provides an equal and standard scanning process framework that would minimize its impact on cargo handling and supply chain.

8.4. Supply chain analysis and economic assessment of the transportation of dry and reefer cargo

Academics have been studying port selection criteria during the past decade as port choice plays an essential part in the MarSC. This issue demonstrates that the impact of port choice analysis on the long-term viability of a MarSC should not be overlooked. This research looks at the entire supply chain, including the hinterland leg, port section, and marine route, to assess the economic impact of port choice in this trade route. The TPR CCM is employed as the primary methodology to achieve the objectives of this chapter. It is initiated by applying a data-gathering strategy to get the relevant container flow for major European ports with West-African ports as a destination. Following that, the updated CCM was used to compute the entire cost of the ship and the supply chain cost in the West-Africa-Europe route.

8.4.1. Response to the overarching research question

The goal of chapter seven was to accomplish two aspects. First, to determine which ports in the West European region have the most significant potential container flow that can be called at in the specific round trade route from West-Africa to Europe. Second, to assess the maritime and supply chain costs for the trade route under various scenarios based on (non) transshipment cargo types, different types of the commodity (dry and reefer), and a combination of different (un)loading ports in Europe, the United Kingdom, and other regions such as the Baltic, Northern part of the North Sea, and Ireland.

As a result, the port of Antwerp is the most appealing port in North-West Europe to employ as a key center. Furthermore, London Gateway is the most desirable port to call from the UK ports because it contains the possible cargoes for the backhaul load. From a cost standpoint, it is observed that visiting more ports will slightly increase the overall vessel cost, as opposed to the generalized cost, which varies insignificantly. It can be justified that port charges, cargo handling rate, and cost and space availability play a significant role in this context. The total maritime cost will increase by calling at more ports and higher cargo loading.

However, the generalized cost follows a different pattern. In this cost, the port and hinterland costs of the destination region are essential, but also, these costs at the origin area have a significant impact on the generalized cost as well as the ocean shipping cost. For example, as the selected ports in this chapter (Antwerp, Rotterdam, and Flushing) are in the same range, they face fierce competition to be the central hub for reefer cargo in West Europe; thus, port authorities try to keep the port charges in the same range.

However, taking Lille (France) as an example, the hinterland cost from the port of Antwerp has the lowest value, while this cost from Rotterdam is the most. As the port costs in African-origin ports are the same, that's why the port of Antwerp presented the lowest generalized cost almost in all European regions.

Therefore, it can be concluded that for all the ports around the world which are situated in the same region and apply the same supply chain process for reefer cargo, not only the lowest maritime and supply chain costs are significant reasons for shipping lines to select a destination port, other factors such as hinterland distance to the warehouse, cargo loading and unloading rate, space availability and congestion at the terminal, competitiveness issues with neighboring ports play a crucial role in port selection analysis.

8.5. Implications on stakeholders

This Ph.D. covered the selected elements of MarSC sustainability and provided the most appealing alternatives and responses regarding economic, environmental, and social issues to each sub-research question and, consequently, the critical research question.
These issues affect the process of the MarSC and require the involvement of all the stakeholders in the maritime industry. It is concluded that MarSC sustainability comprises and integrates three perspectives of people, planet, profit aspects in which all aspects should be taken into account simultaneously to evaluate and improve MarSC sustainability.

This Ph.D. supports the governments and policy-decision makers by providing the costs and benefits of selected cases of addressing the sustainability of MarSC. The applied methodologies and obtained results can be extended to other ports worldwide to address the three dimensions of MarSC sustainability. From a theoretical perspective, two developed models in this Ph.D. are (i) typology and benefit estimation of SRA under BWM and (ii) scanning cost approach for importing containerized cargo. The latter aims to improve security at ports and terminals by enhancing the control and inspection of the cargo and mitigating the smuggling, which leads to an increase in social welfare.

This Ph.D. has established that the economic impacts on vessel owners should be considered to apply green initiatives to progress MarSC sustainability, but the effects on cargo owners and other stakeholders must be considered as well. Moreover, this study confirms that monetary consequences of the sustainability advancements are higher for vessel owners, hence maritime costs, rather than for shippers (supply chain costs). Besides, the obtained results of this dissertation are beneficial for a large group of maritime stakeholders, including logistics operators, shipping companies, shippers, freight forwarders, etc.

Moreover, the thesis contributes to academia by providing a comprehensive literature review on MarSC sustainability initiatives, updating the results of alternative maritime technologies and sustainability practices in compliance with environmental regulations and social issues, and involving different stakeholders in the industry.

8.5.1. Implications of the installment of the SRA under the BWMC

The outcomes are an overview of the economic effects of the foundation of an SRA, particularly from the policymakers' perspectives and ship owners, by providing an evaluation of the potential benefits of not treating the BW between the ports of the region. This paper supports the governments and policy-decision makers by providing the costs and benefits of a possible SRA exemption to the BWM in the North Sea region, which can be extended to the other ports and areas all over the map and be a foundation for further investigations in BW concept.

Also, the results are beneficial for the vessel owners and port authorities by showing the cost savings of treating BW with a shore-based system in different ports between the Netherlands and Belgium. Shipowners understood that regardless of the total net benefit of setting up an SRA, they need to have their own BW treatment system; thus, an onboard installation is unavoidable.

Furthermore, it benefits academia and scholars by introducing the methodology to calculate the costs and benefits of establishing an SRA and developing a typology of vessel types based on yearly BW consumption. Next, it enriches the literature by offering a comprehensive review regarding the risk assessment methods, the most applied BW treatment systems, and recent studies in BWM Convention.

In this research, policymakers are political organizations and public port authorities responsible for providing ecological assessment, classified data, and implementation of SRA in the specified region. In addition, from a political point of view, the performance of an SRA might be hampered by insufficient support from the shipping industry. Also, an ecological risk would have been problematic, causing the size of the eventual SRA to decrease, making it less attractive.

8.5.2. Implications of alternative technologies to mitigate sulfur emissions

This chapter compares the findings of prior studies and, for the first time, considers the shippers' perspective in the economic evaluation of LNG and scrubber technologies by analyzing the generalized chain cost. The latter analysis reveals how alternative options will affect generalized chain costs and which option will deliver the lowest generalized chain cost, impacting policy makers and giving logistics operators a clear picture of which alternative solutions to adopt.
The outcomes are beneficial for logistics operators, legislation regulators, and academia. For logistics operators and, in particular, for shippers, the results allow making the most rewarding investments from an economic point of view and affirm the importance of different technologies on the generalized chain cost.

For port authorities, it is essential to know which solution gives the best socio-economic cost returns. Moreover, they need to consider the bunkering infrastructure of LNG in future policy-making at the port level as this research showed the cost-saving of LNG as a promising alternative option.

The outcomes of this doctoral thesis are applicable for future regulations of IMO or other international or domestic regulatory agencies for mitigating air pollution such as SO_x and NO_x, GHG emissions, the establishment of new ECA, ballast water treatment system, and management and enhancing the security at the ports.

Due to the growth of maritime shipping, which leads to increased environmental pollutions and social concerns, the upcoming legislation would be stricter to curb these damaging issues. For example, given the need to establish the future ECAs, especially in China, the results of this thesis are beneficial for policymakers, shipping lines, shippers to understand the best alternative options in compliance with environmental regulations.

Moreover, the thesis also has a positive impact on the current and future regulations of GHG. LNG was economically assessed for sulfur emissions in this thesis, and given the fact that LNG can reduce CO_2 emission by 20–25%, this fuel complies with GHG regulations to be evaluated as further research.

For scholars, it significantly contributes to the extant knowledge by developing a holistic review of alternative methods according to environmental regulations for mitigating air pollution and GHG emissions caused by the maritime industry. Furthermore, the obtained results allow for a remarkable comparison with other studies on the same topic and include an updated clear direction that may promote the MarSC's sustainability and form the basis for empirical investigation.

8.5.3. Implications of enhancing the supervision of maritime container supply chain

The study indicates that technology can positively affect current processes to enhance the supervision of the container supply chain. From a technological point of view, three types of technology domains are considered in this study: Imaging via X-ray system, electromechanical techniques, and AI. As a result, it has been discovered that no one technical domain has the lowest cost impact, which can be achieved by merging various technological fields. The same effects are observed in all the selected maritime routes, meaning that the financial consequences of applying the existing technologies are higher for vessel owners than cargo owners. Policymakers, such as port authorities, port/terminal operators, and customs brokers could develop plans based on the supply chain platform and handle recognized opportunities and threats.

As the main objective was to evaluate the scanning cost in maximizing the scanning rate and assess its impact on the generalized chain cost at the port of Antwerp, this research assists policymakers in having a more effective decision-making strategy. They can comprehend the implications of maximizing the scanning operation from an economic standpoint and the perspective of the supply chain process at the terminal and port levels. It is critical to evaluate the scanning implications for Antwerp's port's competitiveness with adjacent ports both inside and beyond the country.

8.5.4. Implications of supply chain analysis and economic assessment of the transportation of dry and reefer cargo

As a response to the critical research question, it is observed that by adding more ports in the loop, the ship's total cost (vessel owner's cost) rises moderately while this phenomenon has negligible impacts on the generalized cost (shipper's cost). Thus, it can be concluded that, although supply chain cost should be considered in the supply chain optimization, this is not a decisive factor and the total maritime cost has a higher priority.

The outcomes raise some significant points regarding the containerized cargo flow between West Africa and Europe based on dry and reefer cargo types. Moreover, several stakeholders in the maritime industry, including policymakers and logistics service providers, benefit from the research outputs as it has consequences for stakeholders in terms of management and policy to better their competitive position. The research outcomes will be beneficial for the shipping lines and shippers. By performing the port analysis in terms of the import/export cargo volume and maritime and supply chain costs, these stakeholders can decide which ports are the best to call at in a specific route, increasing the departure schedule efficiency and reducing departure schedule and the transportation costs.

8.6. Limitations

Despite understanding the costs and benefits of sustainability practices in this thesis, controversy still remains regarding some issues such as data collection approach, developed model, and estimated values. The following sections describe the limitations of each application study which are necessary to be addressed for further research.

The research in chapter four was confronted with some limitations in terms of the lack of data about the BW consumption per vessel type. It means that the accurate data of the BW consumption of each type of vessel calling at the ports were not available directly; therefore, some calculations on the existing data were required. Moreover, due to the lack of data, the actual operational days of the different vessels were estimated. Therefore, some extra calculations were needed to estimate the average BW consumption.

The scope of chapter five was restricted in terms of the choice of ship types and investment costs. Firstly, only containerized vessels are taken into account. Secondly, the average investment cost for LNG propulsion and scrubber systems varies depending on ship type and vessel size. In this research, the average investment cost is considered based on the literature, which means that by increasing the size of the vessel, this average cost increases accordingly; however, in reality, the exact investment cost of each vessel size might be different.

Limitations of the study in chapter six need to be acknowledged, most notably, several cost components are not taken into account, such as: (i) costs of building additional offices for image analysts in the case of increasing the scanning rate are ignored; (ii) for image analysts, there is a lack of knowledge about the property costs (e.g., all equipment needed for an office, including desks, bookshelves, chairs); (iii) costs of building additional physical inspection warehouses for more physical checks are not considered; (iv) lack of information about the costs of the site needed for stacking the lorries with containers after scanning at the gate out for waiting due to image processing; (v) costs of building offices required for staff for the communication process are not taken into account; and (vi) a general assumption was made for the costs related to the automated inspection using AI such as data storage (requiring the storage of a vast number of images), and expenses for the personnel needed to perform the work.

Chapter seven's research limitations pertain to the lack of data on the exact potential market share for dry and reefer cargo flows. This chapter obtained these values based on consultation with a classified company specializing in producing, transporting, and distributing fruit and vegetables. Besides, the hinterland cost in the African regions is not calculated due to a lack of data accessibility. This type of cost must be added to the cost evaluation as a future step.

8.7. Further research

Further research could address several additional issues in the context of MarSC sustainability. First, it would be beneficial to repeat the research questions and methods by addressing and satisfying each application study's limitations. It provides excellent mathematical results which can be comparative with the previous results.

This Ph.D. only assessed the economic impact of sustainability issues on maritime shipping; however, the other two dimensions were indirectly considered as external perspectives. Further research needs to investigate the environmental and social aspects of the applied green practices on MarSC to enrich the sustainability assessment

For instance, in chapter four, it is recommended to combine the objectives and the results of this research with an ecological study. Initially, the risk assessment methods of the G7 guideline of IMO should be performed to provide an experimental result of the natural and invasive distribution of target species within the region.

Also, in chapter five, further study is required to improve the understanding of the socio-environmental impacts of alternative fuels by measuring the polluted emissions of SO_x and NO_X of the containerized vessels using LNG, MDO, and scrubber systems based on the sulfur emission regulations in ECAs. Also, application of the updated figures of external costs of pollutants to evaluate the impact of internalization of external costs on the results would be the subject for further research

In the same concept, supplementary examinations are necessary for chapter six to assess the social impacts of using the new scanning process based on different scanning technologies and locations to determine to what extent this research is practical and feasible to mitigate illicit trafficking in society.

Moreover, as further investigations are necessary to evaluate the developed models and methodologies from a scientific perspective, it would be beneficial to replicate this study in other maritime routes, ports, and countries that seek sustainability improvements in the maritime industry. For example, the research in chapter four might be expanded by considering other neighboring ports such as the UK ports, ports in Germany to realize the impacts of extension of the SRA on the cost-benefit and developed typology. In this case, the results of the ecological study play a significant role in extending or minimizing SRA's size.

On the other hand, in chapter five, further research is required to extend the research objectives regarding this topic by including different types of vessels such as cruise ships and bulk carriers. The reason is that in 2019, 55% of recorded port calls worldwide were passenger ships, followed by tankers and bulk carriers (12%), and general cargo break bulk ships (10%) [38]. The reduction of sulfur emissions of these vessels plays a significant role in compliance with environmental regulations, particularly MARPOL Annex VI. Moreover, other maritime routes such as origin ports in South America to destinations in Europe are valuable to examine. It means that, as chapter five considered two intercontinental origin-destination pairs (Asia and the US to Europe), economic assessment of alternative options in a different maritime route with varying types of cargo and sizes can provide a general and international decision-making solution for the best alternative technology in terms of sulfur emission reduction worldwide.

[38] See chapter two for further info (UNCTAD, 2020).

In addition, it remains to evaluate the economic impacts of other types of alternative fuels such as Ammonia, Hydrogen, Methanol, and Nuclear energy on maritime shipping to meet the environmental regulations. The obtained results can be comparable with the gained knowledge of outcomes of chapter five to select the most suitable alternative fuel.

Moreover, in this chapter, the main goal was the reduction of SO_x pollution in ECA; however, it would be relevant to examine the economic impact of LNG and scrubber systems on GHG, mainly CO_2 emission reduction under the extant IMO regulations in which the obtained results make an outstanding contribution to understanding the economic implications and considering the different environmental adjustments on maritime pollution.

Furthermore, in chapter six, an in-depth estimation of AI should be the subject of further research. As AI has a significant impact on cost reduction in image analysis, the detailed and more accurate evaluation of this technology would result in a higher reliable and more robust conclusion for policymakers and customs administration. Besides, it remains an open question whether the applied technologies and developed models effectively detect other types of illicit trafficking such as weapons, explosives, and radioactive substances, to mention a few. Therefore, further research is needed to examine the scanning process under other sources of threats to validate the existing technologies and advanced methods.

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Appendices

Appendix A

Table A.4.1: Implementation of BWM in different regions

Region	Implementation of BW management
Australia	Under the new legislation, it will be an offense for a vessel to discharge BW in Australian seas unless an exemption covers the discharge or the BW has been appropriately managed by the conduct of an acceptable BWE or by using an approved method of BWM. Vessels visiting Victorian ports must undertake a Ballast Water Risk Assessment (BWRS) on a voyage by voyage basis to assess whether their domestic BW is either high or low risk and must not discharge BW until written permission has been granted to do so.
Caspian Sea	Vessels originating from outside the Caspian Sea may treat BWE before leaving the Black/Azov and Baltic Seas. BW would be managed with this measure before inbound vessels enter the waterways connecting to the Caspian Sea.
Central America	No BW operation is permitted in the Panama Canal, which is more related to avoiding blocking the canal and not risking machinery failure. A similar rule exists for the other two major shipping canals in the world – the Kiel and Suez Canals.
China	Any BW discharges are to be avoided in Chinese waters. In situations where BW operations are unavoidable, a tank-to-tank transfer is used.
Malaysia	Ships constructed in or after 1st June 2012, which have a BW capacity of 5,000 cubic meters or more shall conduct BWM to, at least, meet the D-2 standard. It applies to all ships calling at Malaysian ports inside its Exclusive Economic Zone after operating on the waters beyond its Exclusive Economic Zone during any part of its voyage.
New Zealand	Vessels that uptake BW outside New Zealand waters can only discharge in New Zealand waters with the approval of an inspector. If a ship entering New Zealand waters has a type-approved BWMS onboard, the D-2 standard will apply to the discharge.
Persian Gulf	BWE or treatment with a certified BWMS is required for all ports in the Persian Gulf region.

Source: Own composition based on Lloyds Register 2011; Malaysia Shipping Notice 2012; EPA VIC 2012; David and Gollasch 2015

Table A.4.2: Benefits of vessels calling at the Dutch and Belgian SRA ports

Ship type	Ship size	BW consumption per call	Number of calls	Total ballast water not handled	Saved cost
		[tons/call]	[-]	[tons/year]	[EUR/year]
Port of Rotterdam					
Product tanker	< 60000 dwt	258,72	698	180,588	1,354,409

Handysize	<35000 dwt	254,17	8	2,033	15,250
Small Feeder	< 1000 TEU	87.68	63	5,524	41,431
Feeder	< 2000 TEU	131,53	97	12,758	95,685
Feedermax	< 3000 TEU	219,21	102	22,359	167,695
General cargo	All types	32.03	146	4,677	35,074
Gas carriers	All types	234,88	0	-	-
Chemical	All types	57.64	13	749	5,620
		Total	1,127	228,689	**1,715,164**
Zeeland Seaports					
Product tanker	< 60000 dwt	258,72	538	139,192	1,043,943
Handysize	<35000 dwt	254,17	15	3,813	28,594
Small Feeder	< 1000 TEU	87.68	18	1,578	11,837
Feeder	< 2000 TEU	131,53	1	132	986
Feedermax	< 3000 TEU	219,21	4	877	6,576
General cargo	All types	32.03	164	5,253	39,398
Gas carriers	All types	234,88	75	17,616	132,118
Chemical	All types	57.64	169	9,742	73,063
		Total	984	178,202	**1,336,517**
Port of Antwerp					
Product tanker	< 60000 dwt	258,72	14	3,622	27,166
Handysize	<35000 dwt	254,17	12	3,050	22,876
Small Feeder	< 1000 TEU	87.68	51	4,472	33,539
Feeder	< 2000 TEU	131,53	31	4,077	30,580
Feedermax	< 3000 TEU	219,21	181	39,677	297,576
General cargo	All types	32.03	226	7,239	54,293
Gas carriers	All types	234,88	1	235	1,762
Chemical	All types	57.64	492	28,361	212,705
		Total	1,008.00	90,733	**680,496**
Port of Zeebrugge					
Product tanker	< 60000 dwt	258,72	282	72,960	547,197
Handysize	<35000 dwt	254,17	0	-	-
Small Feeder	< 1000 TEU	87.68	0	-	-
Feeder	< 2000 TEU	131,53	0	-	-
Feedermax	< 3000 TEU	219,21	3	658	4,932
General cargo	All types	32.03	51	1,634	12,252
Gas carriers	All types	234,88	20	4,698	35,232
Chemical	All types	57.64	3	173	1,297
		Total	359,00	80,121	**600,909**
Port of Ostend					
Product tanker	< 60000 dwt	258,72	0	-	-
Handysize	<35000 dwt	254,17	0	-	-

Small Feeder	< 1000 TEU	87.68	0	-	-
Feeder	< 2000 TEU	131,53	0	-	-
Feedermax	< 3000 TEU	219,21	0	-	-
General cargo	All types	32.03	6	192,19	1,441.41
Gas carriers	All types	234,88	0	-	-
Chemical	All types	57.64	6	345,86	2,593.96
		Total	12.00	538,05	**4,035**

Appendix B

This section describes the cost parameters of each vessel applied to the scenarios along with maritime cost components in the US-EU route.

Table B.5.1: Running cost of vessel size 4,600 TEU [EUR/hour]

Cost Parameter	Running on MDO	Running on LNG	Running on HFO with Scrubber
Crew	125.89	138.479	151.068
Insurance	62.05	62.05	62.05
Repair and Maintenance	16.27	17.897	19.524
Management and administration	24.71	24.71	24.71
Stores	7.15	7.15	7.15

Table B.5.2: Running cost of vessel size 5,466 TEU [EUR/hour]

Cost Parameter	Running on MDO	Running on LNG	Running on HFO with Scrubber
Crew	125.89	138.479	151.068
Insurance	65.03	65.03	65.03
Repair and Maintenance	16.27	17.897	19.524
Management and administration	24.71	24.71	24.71
Stores	7.15	7.15	7.15

Table B.5.3: Running cost of vessel size 9,115 TEU [EUR/hour]

Cost Parameter	Running on MDO	Running on LNG	Running on HFO with Scrubber
Crew	125.89	138.479	151.068
Insurance	96.78	96.78	96.78
Repair and Maintenance	16.27	17.897	19.524
Management and administration	24.71	24.71	24.71
Stores	7.15	7.15	7.15

Table B.5.4: Running cost of vessel size 13,892 TEU [EUR/hour]

Cost Parameter	Running on MDO	Running on LNG	Running on HFO with Scrubber
Crew	125.89	138.479	151.068
Insurance	139.72	139.72	139.72
Repair and Maintenance	16.27	17.897	19.524

Management and administration	24.71	24.71	24.71
Stores	7.15	7.15	7.15

Table B.5.5: Running cost of vessel size 18,800 TEU [EUR/hour]

Cost Parameter	Running on MDO	Running on LNG	Running on HFO with Scrubber
Crew	125.89	138.479	151.068
Insurance	172.31	172.31	172.31
Repair and Maintenance	16.27	17.897	19.524
Management and administration	24.71	24.71	24.71
Stores	7.15	7.15	7.15

Figure B.5. 6: Share of maritime cost components based on sensitivity analysis – 9,115 TEU – US - EU

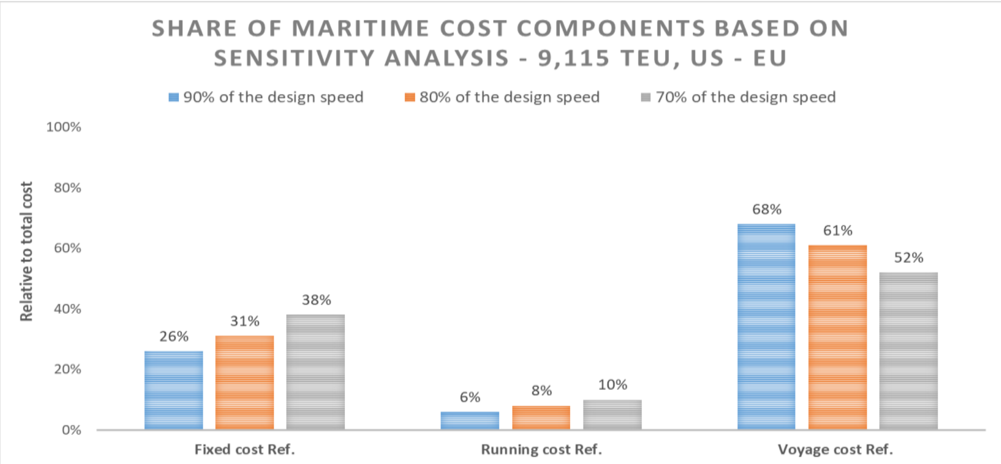


Figure B.5. 7: Changes in maritime cost components for reference and LNG scenarios – 9,115 TEU – 90% of design speed – the US - EU

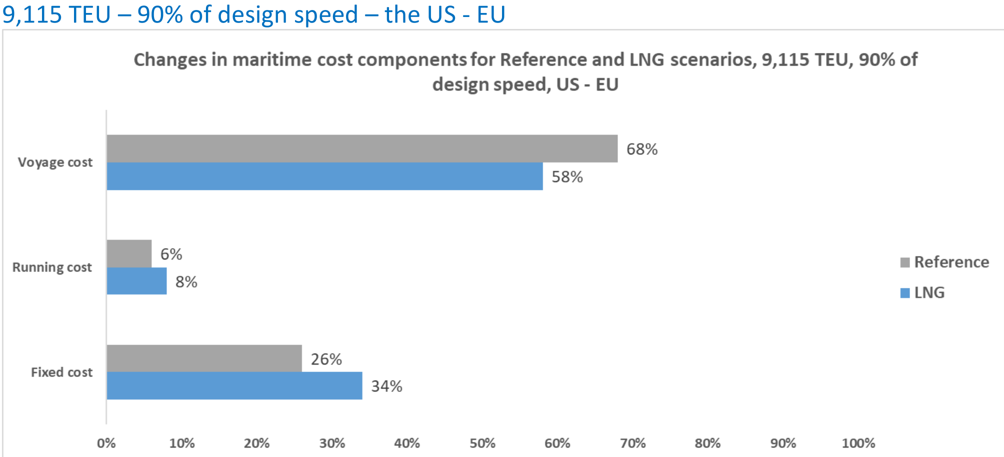
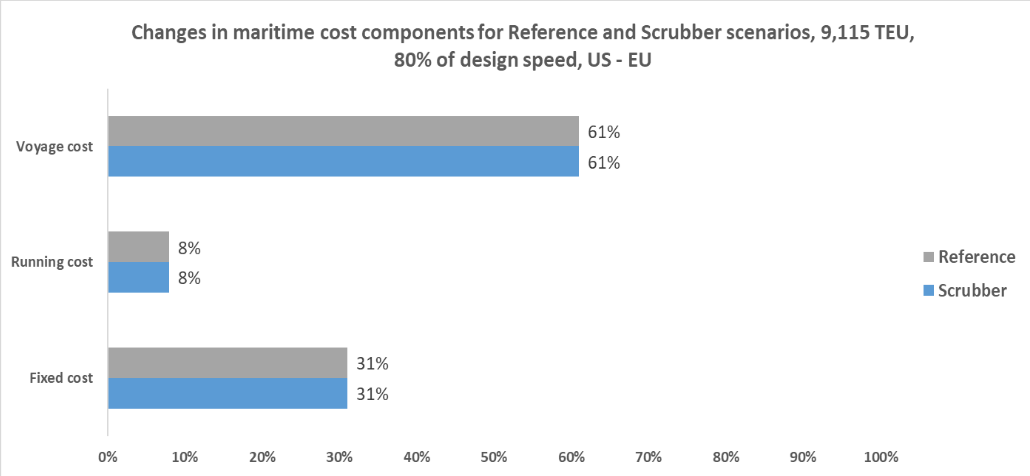


Figure B.5. 8: Changes in maritime cost components for reference and Scrubber scenarios – 9,115 TEU – 80% of design speed – the US - EU



Appendix C

C.1. European Ports to Antwerp:

Figure C.6. 1: Generalized chain cost from Felixstowe to Antwerp

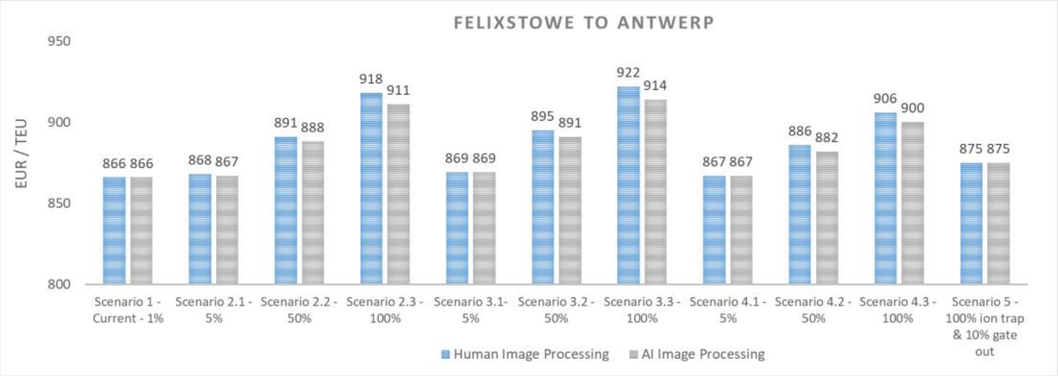
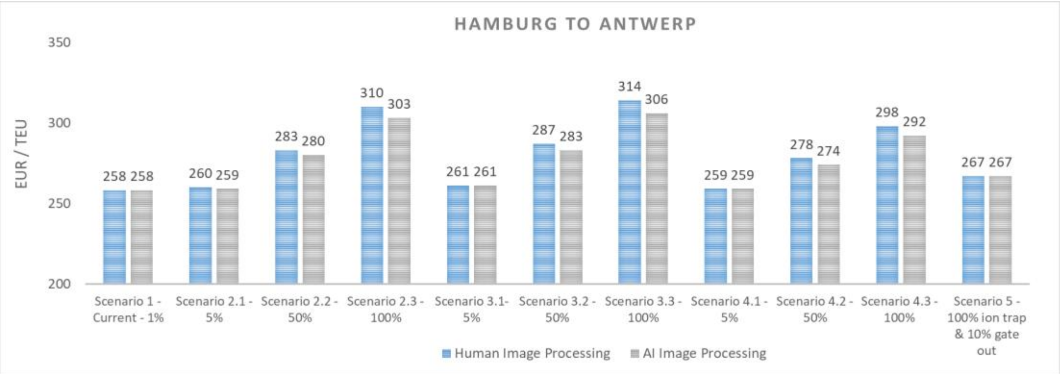


Figure C.6. 2: Generalized chain cost from Hamburg to Antwerp



C.2. Asian Ports to Antwerp:

Figure C.6. 3: Generalized chain cost from Hong Kong to Antwerp

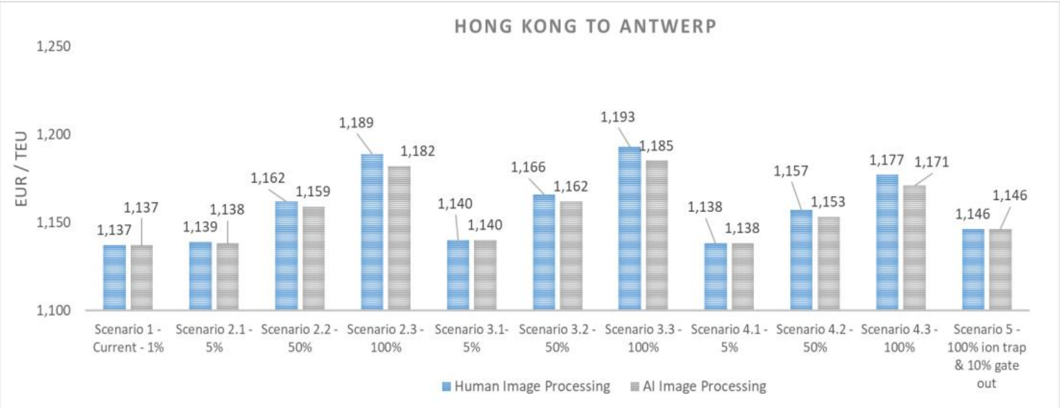


Figure C.6. 4: Generalized chain cost from Shanghai to Antwerp

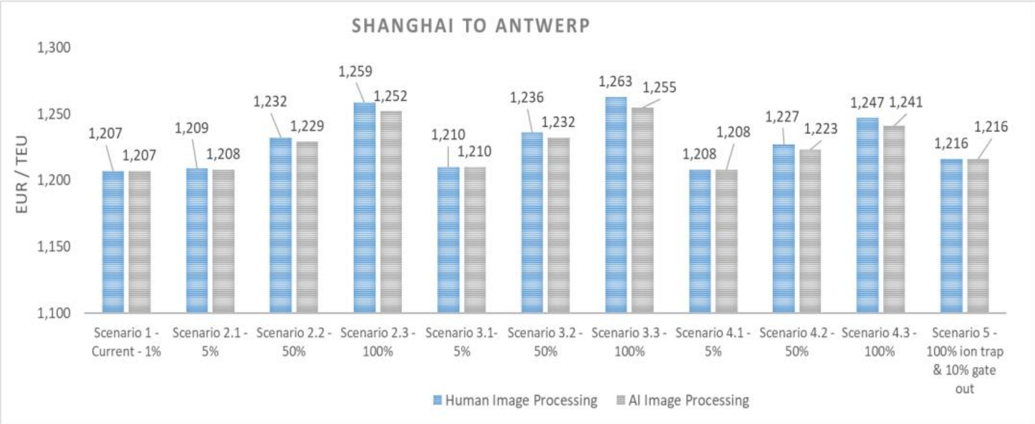
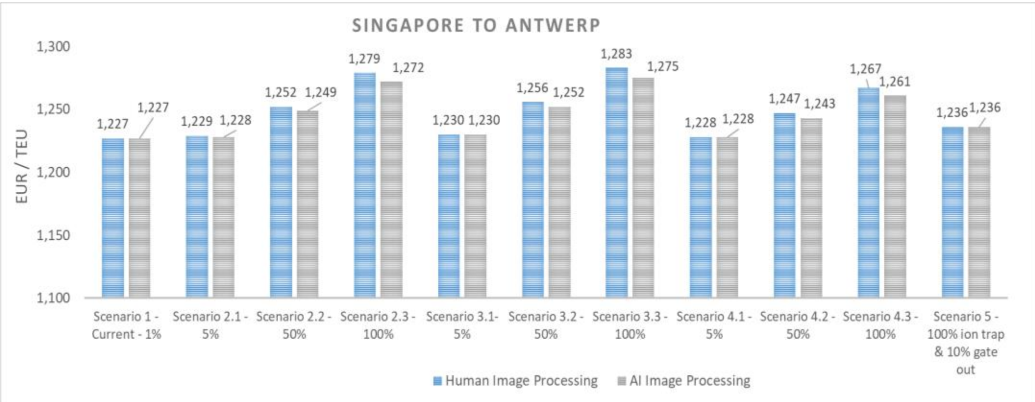
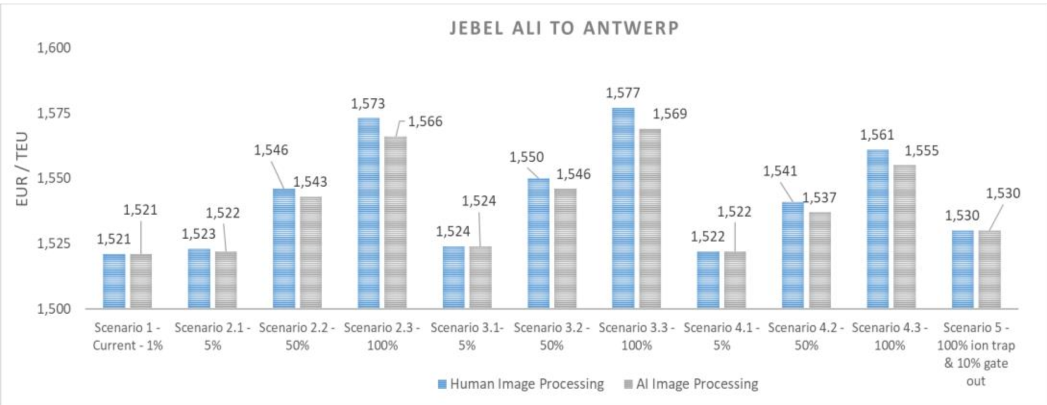


Figure C.6. 5: Generalized chain cost from Singapore to Antwerp



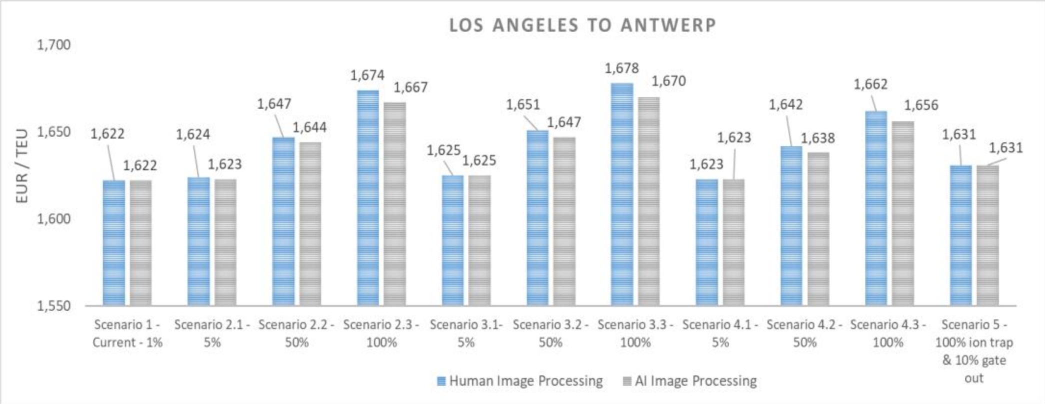
C.3. Middle East Ports to Antwerp:

Figure C.6. 6: Generalized chain cost from Jebel Ali to Antwerp



C.4. North American Ports to Antwerp:

Figure C.6. 7: Generalized chain cost from Los Angeles to Antwerp



The obtained results for each of these ports reveal that the generalized chain cost would grow by increasing the scanning rate. Moreover, scenario 5 displays better results compared to the other scenarios.