Socio-economic evaluation of alternative technologies to mitigate Sulfur emissions in maritime container transport

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Abstract

International maritime shipping has been affected by a lot of new legislative actions of several policy actors (i.e. IMO, the EU) from 2006, onwards to 2030, in order to improve the ecological performance of maritime shipping. Several policies are directly related to reducing the pollution levels of vessels both globally and locally in the so-called Emission Control Area (ECA). In this research, the impact of the installed ECA zones, to reduce the Sulfur emissions near coastal areas, for maritime container transport is analyzed.

In order to respect these new legislative actions container shipowners can opt for different methods to comply, such as switching fuel types (LNG, low Sulfur fuel (MDO)) or to opt for alternative technologies such as scrubber systems. These different options are examined economically, both from the perspective of the vessel owner as well as for the evaluation of generalized chain cost, hence from the shipper point of view.

The analysis uses a model designed for calculating the generalized cost of transporting a container from origin to destination. It can simulate both the vessel owner cost as well as the generalized cost of a supply chain for transporting goods from a point in hinterland A (e.g. in the US) to another point in hinterland B (e.g. in Europe). To study the impact of the implementation of the considered option to fulfill the new types of legislation, this model has been extended with a module to calculate the vessel related cost (vessel owner perspective). Next to that, also more detailed maritime distance data (ECA zones distances) is incorporated as well as a more detailed fuel and capital cost calculation to account for the three above-mentioned options. The calculations allow deriving the best (socio)economic solutions for specific routes. The results indicate that the price of the different fuels (and the spread between them) display an important factor in the overall outcome.

Keywords: Alternative fuels; LNG propulsion; scrubber system; marine diesel oil; ECA zones; maritime cost; chain cost.

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). A significant part of this comes from the maritime transport sector (Colvile et al. 2001). Emissions from shipping due to the burning of the Sulfur content of marine fuels conduce to air pollution in the form of Sulfur dioxide and particulate matter (Sys et al. 2012). Moreover, international marine shipping is a large contributor to NO_x and SO_x emissions, representing a share of 13% and 12% of global emissions respectively (IPCC, 2013; Stevens et al. 2015).

Since 2006 regulations derived from the International Convention for the Prevention of Pollution from Ships (MARPOL Annex VI) affected the international marine shipping regarding reducing the pollution. This means that maximum level of pollution of Sulfur oxides and nitrogen oxides globally and within Emission Control Area (ECA) zones, in particular, are set (Trozzi, 2010; McGill et al. 2013). 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. Moreover, Annex VI contains provisions for two sets of emission and fuel quality requirements regarding SO_x and PM, or NO_x, a global requirement and more stringent controls in special Emission Control Areas (ECA), (IMO, 2011). According to IMO (2011) and McGill et al. (2013), as of 2011, there are four existing ECAs: the Baltic Sea, the North Sea, and the North American ECA, including most of the US and Canadian coast and the US Caribbean ECA. Also,

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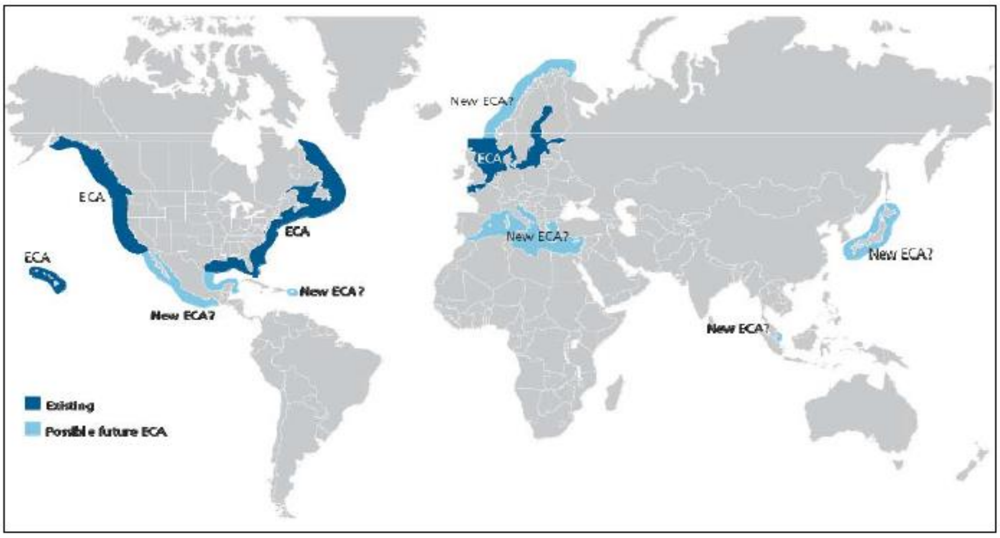
other areas may be added via the protocol defined in Annex VI. The current and probable future ECA zones are plotted in figure 1.

Fig. 1. Current and possible future ECAs



Source: IMO (2011) and McGill et al. (2013)

In van Hassel et al. (2016) a study has been done with respect to the installment of the ECA zones at the North Sea and how this ECA could offset the competitive position of the Hamburg – Le Havre (HLH) range ports to the Mediterranean ports. In this research, the way to mitigate the ECA zones in the North Sea by shipowners was to MDO. In the analysis, two different routes were analyzed (one from Asia to EU and one from South America to the EU). From the preformed analysis was concluded that the competitive position of the HLH ports was not affected by the installment of the ECA zones. It was also found that different routes led to slightly different impacts.

In this research, we want to add to research by shifting the focus of the analysis from the port range competition to the vessel owner and the shipper. The main purpose of this research is to determine which of all the available options to comply with the ECA zones regulation is most economically suitable for the vessel owner and the shipper. The main research questions that will be researched are:

- Which alternative options can be used to comply with the ECA zones regulation?
- Of those selected technologies, what are the maritime costs from a shipowner point of view and what is the impact of new technology on the generalized chain cost?

In order to answer these two research objectives, a two-step approach is used. In the first step, an extensive literature study will be made to determine which alternatives are the most suitable to use. In the second step, for the selected alternatives such as Marine Diesel Oil (MDO), Liquefied Natural Gas (LNG) and scrubber technology a cost modeling approach will be applied. This analysis uses a model designed for both calculating the total vessel owner cost as well as the generalized cost of transporting a container from origin to destination. It can simulate both the total vessel owner cost as well the generalized cost of a supply chain for transporting goods from a point in hinterland A (e.g. in the US) to another point in hinterland B (e.g. in Europe). To study the impact of the implementation of the considered implemented technologies to fulfill to the new types of legislation, this model will be extended with more detailed maritime distance data (ECA zones distances) as well as a more detailed cost calculation, which includes the three above-mentioned options.

This paper is structured in the following parts: in the second section, the literature review regarding available alternative fuel options and economic comparison of technologies is reported. The third section provides the modeling methodology. Section 4 provides an overview of the collected data. In section five, the results obtained for total maritime cost and chain cost and discussions are reported. Finally, in the last section, the main outcomes and conclusions are outlined.

2.1. Emission legislation

Different international organization (i.e. IMO) and institution policies impose international environmental standards on their member states to limit the emission of greenhouse gases (Sys et al. 2012). The regulation stems from concerns about "local and global air pollution and environmental problems" about the shipping industry's contribution. In July 2010, a revised and more stringent Annex VI was enforced in the Emission Control Areas with significantly lowered emission limits (McGill et al. 2013). Based on the literature, there are some emission legislations for international shipping in order to reduce SO_x and NO_x pollutants. 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 1.

Table 1: MARPOL Annex VI marine So_x emission reduction areas with fuel Sulfur limits

Sulfur Emission Control Areas	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 2012	3.5	35,000
	As of 2020*	0.5	5,000

*Alternative date is 2025, to be decided by a review in 2018.

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

Inside ECA areas, limits for SO_x and PM are reduced from 1% (since 1 July 2010) to 0.10%, effective from 1 January 2015. Moreover, the Sulfur content of any fuel used on board a ship must be reduced to 0.5% from 1 January 2020 (Trozzi, 2010; IMO, 2011; Stevens et al. 2015; McGill et al. 2015). In addition, ships operating in the ECAs must respect the MARPOL Annex VI Marine Tier III NO_x limits in 2016. Table 2 shows the applicable NO_x limits for ships and the dates that they became or will become effective (Trozzi, 2010; IMO, 2011; McGill et al. 2013; Perera and Brage, 2016).

Table 2: MARPOL Annex VI NO_x emission limits

		NOx limit,		
Year	**Tier**	**$n < 130$**	**$130 \leq n < 2000$**	**$n \geq 2000$**
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 NOx emission control areas (Tier II standards apply outside ECA's).

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

From table 2, it is clear that the legislation values rely on the rated engine speeds (n) given in RPM (revolution per minute). The NO_x legislation applies to diesel engines (>130 kW) installed on a ship constructed on or after 1 January 2000 and prior to 1 January 2011 for Tier I, while Tier II applies to diesel engines (>130 kW) installed on a ship constructed on or after 1 January 2011 and Tier III is for diesel engines (>130 kW) installed on a ship constructed on or after 1 January 2016. It should be mentioned that Tier I and Tier II limits are global, whereas the Tier III standards apply only in the NO_x ECAs (Trozzi, 2010; IMO, 2011; McGill et al. 2013).

IMO and EU policies require ship operators to reduce the Sulfur emissions of their ship operations. Ships operating in a Sulfur Emission Control Area (SECA) need to use distillate fuels in these regions, or a technology that can reduce emissions to an equivalent level, as of January 1, 2015. There are several options available to comply with the new limits, including Marine Gas Oil (MGO); LNG; Heavy Fuel Oil (HFO) + scrubber (den Boer and Hoen, 2015). According to Semolinos et al. (2013), shipowners have only three realistic alternatives to achieve compliance with the SO_x regulations: using MDO, installing scrubbers on board the ships, or convert ships to run on LNG. To meet the NO_x

regulations, only an LNG solution will, in theory, comply with Tier III. Ships will need to install systems to reduce NO_x (like selective catalytic reduction (SCR) systems) if running on MDO or HFO in any case.

2.2. Alternative marine fuels

The use of HFO as marine fuel poses serious environmental and economic risks (Roy and Comer, 2017). In 2013, McGill et al. stated that the large part of the marine fuel consumption (approximately 77%) is of low quality, low-price residual fuel also known as heavy fuel oil, which tends to be high in Sulfur. With stricter emission rules and more public focus on maritime transport, reducing emissions in a cost-efficient way has become a necessity for shipping lines (Lindstad et al. 2015). Market penetration by alternative fuels has already begun with shipbuilders, engine manufacturers, and classification bodies by introducing greener ships running on cleaner fuels (Moirangthem et al. 2016).

There is a growing number of shipboard applications of new, alternative fuels such as low Sulfur fuels, gas fuels, and biofuels in the global maritime transport (Kołwzan and Narewski, 2012). Aronietis et al. (2015) state that there are three approaches in order to avoid SO_x in shipping. The first approach is to use Sulfur-free fuels, which can be done through some alternative options; the first alternative is the usage of the more expensive MDO (Marine Diesel Oil) with a low Sulfur content but also with lower viscosity, while the second alternative is using LNG as a fuel. The second approach is to remove the Sulfur from the exhaust gasses by continuing to use the cheap HFO and clean the exhaust gasses on board by means of a scrubber. The third option is to reduce the required fuel volume. An example of this is optimizing the Power Take Off (PTO) on the main gearbox.

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 et al. 2016). Gaseous fuels are divided into oil, industrial and natural gas and according to the state; the gas is divided into LPG, Compressed Natural Gas (CNG) and LNG (Žaglinskis et al. 2018). However, according to McGill et al. (2013), other fuels not included for practical, economical, or safety-related limitations of ships are the following: nuclear fuels (Thorium, Uranium, Plutonium, H_3), wind or solar power (sails, kites, wind turbines, photovoltaic cells), solid boiler fuels (coal, coke, peat, lignite), gas turbine or spark ignition engine specific fuels (kerosene, ethanol, gasoline), gasification fuels (wood and other cellulosic biomass, sludge and other organic wastes) and electrochemical fuels (hydrogen, batteries). In this paper, among all the possible alternative solutions, LNG propulsion, MDO, and scrubber technology are considered and discussed in detail.

2.2.1. Liquefied natural gas (LNG)

LNG is one of the options seen as an alternative fuel for deep sea, short sea and inland navigation ships (Aronietis et al. 2015). Natural gas reduces local air pollutants compared to traditional maritime fuels. LNG in marine transportation is likely to be incentivized where economics favoring natural gas is coupled with air emissions public policy targets (Thomson et al. 2015). Moreover, gaseous fuel available for marine use is natural gas which is not only very low in Sulfur content but they also combust such that NO_x, PM, and CO_2 are reduced (McGill et al. 2013). The general characteristics of LNG propulsion are very important to consider this option as a sustainable solution for emission reduction. In table 3, some of the main positive and negative features of LNG propulsion are summarized according to different sources.

Table 3. Advantages and disadvantages of LNG

Features	Sources									
	MAN Diesel and Turbo (2011)	Kołwzan and Narewski (2012)	McGill et al. (2013)	Stulgis et al. (2014)	Aronietis et al. (2015)	den Boer and Hoen, (2015)	Lindstad et al. (2015)	Moirangthem et al. (2016)	Bauen et al. (2017)	Žaglinskis et al. (2018)
Advantages										
Availability		x	x					x		
Cost*	x	x	x	x			x			
Availability of Marine Gas Engines			x			x				
Lower Exhaust Emissions **	x	x	x	x					x	x
Energy density 60% of diesel		x						x	x	x
Disadvantages										
Not compatible with existing engines and fuel systems***			x	x	x		x	x		
Requires space and adds weight ****			x		x		x	x		x
Future fuel price of LNG is uncertain				x		x				
Limited bunkering infrastructure			x	x				x	x	
Methane slip from larger marine engines burning gas	x		x				x	x		
Flammability and low freezing temperature			x							

Source: own composition based on (MAN Diesel & Turbo, 2011; Kołwzan & Narewski 2012; McGill et al., 2013; Stulgis et al., 2014; Aronietis et al., 2015; den Boer and Hoen, 2015; Lindstad et al., 2015; Moirangthem & Baxter, 2016; Bauen et al., 2017; Žaglinskis et al., 2018).

*Cost competitive with residual and distillate fuels. **Carbon emissions by 25%, SO_x by 100%, NO_x by 85% and PM by 95%. ***Requires the modification of existing engines, additional training, and certificates, investment or retrofit costs, safety requirements. ****LNG fuel takes up twice as much space as liquid fossil fuel and reduces the earning capacity of the vessel.

It can be observed from the above table that the advantages and disadvantages for LNG are not the same for each paper and it depends on the research conducted by each author. The above table states that, regarding advantages of LNG, reduction of pollutants such as SO_x, NO_x, and PM is the most significant factor which most of the authors mentioned. Then, cost competitiveness with distillate and residual fuels and energy density are the second and third most important features respectively. However, the negative aspects of LNG propulsion are categorized firstly as a problem with compatibility with existing engines, which increases the operational and retrofit costs and requirements of more space and weight. Following that, methane slip from engines burning gas and limited bunkering infrastructure are other important disadvantages of LNG propulsion considered by most of the authors.

2.2.2. Marine diesel oil (MDO)

According to Van Rynbach et al. (2018), the simplest option for meeting the upcoming low Sulfur limits is to burn MGO with Sulfur content at or below 0.1% in the ECA 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). Van Rynbach et al. (2018) found that the price of MDO typically costs about 50% to 70% more than HFO. Availability of marine diesel oil in the future is another negative feature (Semolinos et al. (2013). There have been some difficulties in existing ships with the change over from heated HFO to cool MGO when entering or leaving an ECA. Semolinos et al. (2013) state that the level of investment needed is much lower than for LNG and the feasibility therefore higher.

2.3. Exhaust gas treatment systems

International maritime legislation is shifting towards lower levels of permitted exhaust gas Sulfur oxide emissions from ships (Lahtinen, 2016). Another option to lower emissions and comply with regulations within ECA zones is installing "scrubber" technology. Scrubbers allow ships in the ECAs to continue to burn traditional bunker fuel, yet still benefit from the savings created by the price difference between (cheaper) traditional 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 and Hoen, 2015). According to Aronietis et al. (2014), an exhaust gas scrubbing system can reduce the level of Sulfur dioxide in the exhausts of ship engines, but at the same time, the energy consumption increases. Some features of this technology are: reduction of NO_x, PM and SO_x emissions (emission of Sulfur is reduced by more than 90%, PM emissions by 60-90%, and emission of NO_x by 10%), loss of cargo capacity due to the large physical size of the systems, no reduction of CO_2 emissions, additional GHG emissions range between 1.5 and 3%, increase of fuel consumption, disposal need of a Sulfur-rich sludge waste, requires 0.75% to 2.5% of the energy of the main engine, extra operating and investment costs (McGill et al. 2013; Chryssakis et al. 2014; Stulgis et al. (2014); Aronietis et al. 2015). Four main principles of exhaust gas scrubbing exist open loop, closed loop, dry and hybrid scrubbers (McGill et al. 2013; Aronietis et al. 2014; den Boer and Hoen, 2015; Lahtinen, 2016). In table 4, a brief description of each is reported.

Table 4. Different scrubber systems and relevant features

Open loop seawater scrubbers	Water and Sulfur react to form Sulfur acid, which is neutralized with alkaline components in the sea water. Filters separate particles and oil from the mixture before the cleaned water is sent back into the sea. It typically uses seawater as the scrubbing medium and requires relatively large space on board. The negative characteristic of an open loop system is its greater energy consumption compared to a closed loop system, but there is no need for chemical additives like caustic soda in a closed loop system. Increase of sulfur in seawater would impact the water quality.
Closed loop scrubbers	This type uses freshwater with the addition of an alkaline chemical (such as caustic soda). Therefore, no wash-water is produced that would have to be pumped into the sea. This type requires more space than open loop systems.
Dry scrubbers	It uses a dry chemical, such as calcium hydroxide and Sulfur is locked in, meaning it cannot burden the biosphere at sea anymore. It does not use any liquids in the process but exhaust gases are cleaned with hydrated lime-treated granulates. Exhaust gas flows through granulated limestone. It combines with the Sulfur to form gypsum, which can then be disposed of on land. The storage room has to be created on board for granulate, which reduces cargo capacity. An advantage of a dry scrubber is its lower energy consumption compared to a wet scrubber.
Hybrid scrubbers	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 is operating in the open sea and as a closed loop system when operating in harbor or estuaries, where water discharge is prohibited.

Source: Own composition based on (McGill et al., 2013; Aronietis et al., 2014; den Boer and Hoen, 2015; Lahtinen, 2016)

According to Alphaliner (2018), scrubbers are more popular than LNG fuel as an alternative to comply with the new SO_x limits, with only 13 LNG powered units expected ready while the number of scrubber-fitted container ships is expected to come close to 200 units by January 2020 when the IMO’s global SO_x limit is reduced to 0.5%. Despite increased interest from shipowners for scrubbers and LNG, the total number of such IMO compliant ships will only be a fraction of the total containership fleet. The vast majority of ships will need to switch to low Sulfur bunker in 2020.

2.4 Economic comparison of alternative technologies

Based on the literature review, there are some sources, which compared different alternative technologies from an economic perspective. In the following section, the approach they used, and the general conclusions of each paper are reported.

Man diesel and Turbo (2011) have done research in order to compare some alternative technologies. The main purpose of this study is to trigger by shipowners interested in LNG as ship fuel, which is currently facing a number of questions regarding costs and possible benefits of using such technology. They intend to know if exhaust gas treatment systems could be the preferred technical solution. The study assumes costs for key technologies when applied to five differently sized container vessels, and predicts their benefits in comparison to a reference vessel, which uses fuel required by existing and upcoming regulations depending on time and location of its operation. Hence, the reference vessel uses MGO when inside the ECA zones by 2015 or within EU ports. Outside the ECA zones, HFO is used and a Low-Sulfur Heavy Oil (LSHO) with a 0.5% Sulfur content by 2020. Moreover, five representative container vessel sizes were selected for the study (2.500, 4.600, 8.500, 14.000 and 18.000 TEU). Round trips were selected for three trades: intra-European, Europe-Latin America and Europe-Asia. The ECA exposure is used as a primary input parameter. From the study is concluded that the use of LNG as a ship fuel promises a lower emission level and, given the right circumstances, lower fuel costs. The attractiveness of LNG as a ship fuel compared to scrubber systems is dominated by three parameters: investment costs for LNG tank system, price difference between LNG and HFO, and share of operation inside ECA. For smaller vessels, a comparison of payback times for the scrubber and for the LNG system, and varying LNG prices shows that the LNG system is attractive as long as LNG (delivered to the ship) is as expensive as or cheaper than HFO, when the fuels are compared on their energy content.

Aronietis et al. (2014) have done research to investigate the selection of the best retrofit solutions for the Ro-Ro and Ro-Pax ships. It is done by creating an aggregate simulation model that simulates the impacts retrofit solutions would have if they were implemented in the market. From the research is concluded that speed reduction brings the most benefits. The economic benefits that can be observed for this technology are probably one of the main reasons why speed reduction is a commonly used practice. Scrubbers perform well economically, but the emission and energy performance is worse than that of the other technologies. The emission performance of the dual-fuel engines, which in normal operation are assumed to run on LNG, is also very good. For dual-fuel engines, the high investment costs are the reason for the bad economic performance, although the emission performance is very good. The economic performance of voyage optimization and enabling PTO/PTI to improve loading of the engine is good due to low investment costs.

Research by Hsu et al. (2014) is related to possible alternative solutions such as MGO, LNG, and scrubber system, Methanol (Me OH) regarding the legislation Marpol Annex VI for SO_x emission regulation in ECA zones Baltic Sea, North Sea, North America, and Caribbean. The approach used in the paper is life-cycle cost analysis, which includes different stages such as planning, design, construction, operation, and end of life.

In the approach, three key elements are environmental, economic and technical issues during each stage. The vessel types that are included are Ro-Pax (1300 passengers and 300 cars), cruise vessel (3080 passengers), container feeder (1700 TEU) and small ferry (600 passengers and 160 cars). The following costs are considered in the model: capital cost, installation cost, operation cost, maintenance cost, and total life-cycle cost. Data are collected for the initial cost (engine, equipment and installation cost); the operations cost (ship fuel consumption rate, route, operation working condition, average load, and future fuel price). The model is applied for a duration of 15 years (from 2013 until 2028) by the estimation of fuel prices by considering an escalation rate of 5%. By comparing the current price of fuels, it is obtained that MGO is the most expensive one while methanol is on the second place and HFO and LNG are the cheaper ones respectively. The conclusions obtained from the paper are: the fuel price has a significant impact, LNG, scrubber are better for a long life cycle, and methanol is better for a short life cycle.

DNV GL and MAN Diesel and Turbo (2016) have done a joint study to analyze costs and benefits of various fuel options for a case with one particular ship and its operating pattern. The alternative fuels selected are LNG, LPG, methanol and new ultra-low-Sulfur fuel oil, a so-called hybrid fuel. Costs and benefits for a newbuild are determined by looking at its additional investment and operating costs compared to a standard fuel variant using HFO and MGO (HFO outside of SECA and MGO inside). An LR1 product tanker on a fixed route is selected to perform a financial analysis. Features of vessels are length overall: 225m, breadth: 32.26m, main engine: 1 x MAN B&W 6G60ME-C-9.5, NCR (90% SMCR): 10390 kW, design speed at NCR: 15 knots. The ship is assumed to operate on a route between Northern America and Northern Europe: Houston-Rotterdam; Ventspils-Houston. From the total distance of about 11,700 nautical miles, approximately 37% is inside the SECA. The comparisons are made with two different scenarios of fuel prices; A high price scenario based on the fuel prices in mid-2014, at a time when the Brent oil prices were 100-110 $/barrel, and a low price scenario based on fuel prices in mid-2015 when the Brent oil prices were about 50 $/barrel. Generally, the scenario with the highest absolute fuel prices resulted in the highest price difference between traditional and alternative fuels. Consequently, the high price scenario resulted in the highest annual cost difference for the alternatives as well as the shortest payback times. With the two price scenarios used in this study, methanol and ultra-low-Sulfur fuel oil do not show a financial feasibility. LNG and LPG are both financially interesting alternative fuels, and LPG are found to be at least as good as LNG. For these best fuels, the best alternative is to use it both inside and outside SECA regions. For LPG, it is recommended to consider full round trip endurance for the tank system.

Newman (2017) states that LNG is the alternative shipping fuel, reducing emissions by up to 100% for SO_x, 90% for NO_x and 25% for CO_2, which emits few particulates. In the research, an example calculation of an 8.500 TEU container ship is fulfilled by four different scenarios for container ships: LNG newbuild, MGO, scrubber, and LNG conversion. The capital expenses (CAPEX) and voyage expenses (VOYEX) are based upon a generic 8.500 TEU container ship, with the following particulars; trade: Rotterdam to Shanghai // Shanghai to Rotterdam; speed: 23.5 Knots with a specific fuel consumption (SFC): 200 tons per day; engine power: 52,000 KW; port consumption: 10 tons per day. By comparing the obtained results of total voyage cost of all four scenarios, Newman (2017) found that scrubbers have the lowest cost, then LNG for newbuild ships is on the second, and MGO and LNG conversion ships are located on the third and fourth places respectively. The results are reported in table 5.

Table 5. Obtained results for each scenario

	Container Ship - LNG newbuild	Container Ship -MGO	Container Ship - Scrubber	Container Ship - LNG conversion
Load	Antwerp	Rotterdam	Rotterdam	Rotterdam
Discharge	Shanghai	Shanghai	Shanghai	Shanghai
Distance (nm)	10664	10664	10664	10664

Sea days	19.85	19.85	19.85	19.85
Total voyage cost -5 years amortization	2,124,909	2,154,656	1,515,017	2,371,484
Ranking	2	3	1	4

Newman (2017) formulates firstly that LNG conversions are not an especially promising option given the sizeable CAPEX involved in procuring the bespoke kit for the project, coupled with the time necessary to take the vessel out of service (loss of hire can be much more significant than the above-mentioned calculation suggests). Secondly, for existing vessels, LNG scrubbers provide a very sound option and indeed, they even outperform a newbuild LNG DF engine in voyage cost terms (based on forwarding pricing assumptions). Third, for all new tonnage ordered from today onwards, however, a newbuild DF LNG propulsion offers the most cost-effective long-term solution, especially considering all existing, planned and potential IMO requirements.

In 2017, Abadie at al. fulfilled research regarding the adaptation of the shipping sector to stricter emissions regulations by either fuel switching or installing a scrubber. In the paper, the focus is solely on the options available to the existing fleet, and therefore consider only the options of switching to low-Sulfur marine fuels and installing a scrubber. The choice of one option or the other depends on various factors such as the price of fuels, the area in which the ship usually operates, the regulations applicable to it, the number of days at sea and the remaining useful lifetime of the ship, among others. Some of these factors are known but others involve a certain degree of uncertainty. In this paper, it is proposed the use of stochastic modeling to deal with uncertainties concerning the price of the different fuels. The paper does not set out mainly to analyze carbon emissions from shipping and slow steaming or reducing the speed of vessels is not considered in this paper. By using the percentage of time that a ship stays in ECAs, the results are obtained which show how many tonnes of fuel are used under each scenario of time at sea using scrubbers and switching fuels for both types of fuel and two points in time: in the initial period (up to the end of 2019) and in the second period (2020 and beyond). Note that in the initial period, when the fuel switching option is considered different percentages of low-Sulfur could be used depending on how long is spent in ECAs. During the second period, low-Sulfur fuel should always be used. By contrast, if scrubbers are installed the ship is allowed to consume high-Sulfur fuels. In this case, the consumption is a little greater than in the fuel-switching case due to the additional energy that is required to operate the scrubber. The information obtained by the result provides an understanding of the effects that variables such as the remaining lifetime of a ship, the percentage of time that vessels spend in ECAs and the percentage of time spent at sea have on investment decisions. Logically, the longer the remaining lifetime of the vessel is, the longer the vessels spend in ECAs and the longer they spend at sea, the more attractive the option of investing in scrubbers becomes. However, it is also noted that when scrubbers are used fuel consumption is higher, so emissions per year are also higher.

The above studies show the comparison of different alternative technologies from shipowner perspective. They compared the LNG propulsion by scrubber technology or other available options for specific ship types and maritime routes, which are beneficial for vessel owners. The missing part of previous studies is that none of them considered the economic impact of the new technologies on the chain cost. Therefore, the objectives of this research is not only economic comparison of three different alternative fuel options from shipowner point of view but also economic assessment of different options from chain cost perspective which shows how alternative options will affect the generalized cost and which option will provide the lowest generalized cost which affects the policymaking process and provides a great view for logistic operators in order to deploy the best alternative solution.

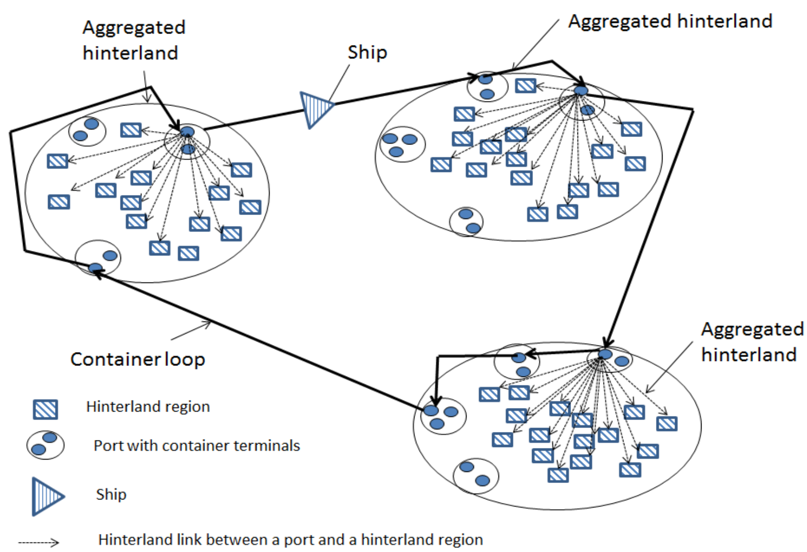
3. Methodology

The starting point for the analysis is the Chain Cost Model, proposed by van Hassel et al. (2016) and has been extended in van Hassel et al. (2016b) and van Hassel et al. (2018). For the purpose of this paper, the model has been further developed and adapted in order to deal with the specific research questions addressed in this paper. Section 3.1 provides a brief overview of the model, its components. Section 3.2 deals with the necessary input parameters. Subsequently, section 3.3 looks at some of the adaptations to the base model.

3.1 Overview of the base model

The purpose of the base Chain Cost Model is to calculate the generalized chain cost per TEU from a selected point of origin in the hinterland, via a predefined container loop, to a destination point in another hinterland. The container loop encompasses the maritime leg of the supply chain. Figure 2 provides a general overview of the original model (van Hassel et al. 2016).

Fig. 2. Conceptual representation of the Chain Cost Model



Source: van Hassel et al. (2018)

In the Chain Cost Model, different aggregated hinterlands are connected via a route along with ports (bold lines in Figure 2). The aggregated hinterlands are defined as a summation of different smaller geographical areas, which in Europe correspond to NUTS-2 areas. Each aggregated hinterland is served by at least one and usually by several ports. Each port is built up of a set of terminals, all of which have their own set of characteristics. From each port terminal, the hinterland connections via road, rail, and inland waterways (if applicable) to all the disaggregated hinterland regions are incorporated into the model (van Hassel et al. 2016).

In the model, a logistics chain is defined as a route from a specific hinterland region (i) to another hinterland region (j). A chain, therefore, has a beginning and an end. The aggregated hinterland in which the origin of the chain is situated is called the aggregated *from*-hinterland (Y), whereas the hinterland where the end of the chain is located is referred to as the aggregated *to*-hinterland (Z) (van Hassel et al. 2016).

3.2. Input parameters

The input for the Chain Cost Model consists of three main elements. The first input is the selection of a container loop. An actual loop can be incorporated in the model using data obtained from the websites of the concerned container lines. In the Chain Cost Model, it is possible to build a container loop for which a database of 70 different ports can be used. Secondly, a specific vessel needs to be selected to sail the specific loop. The main standard input parameters related to the ship are a sailing speed of 22 knots and capacity utilization of 80%. The capacity utilization of inland vessels and trains is assumed 80%. All other input parameters are taken from port and terminal websites and other sources such as Drewry (2015) for the terminal throughputs.[1]

3.3. Adjustments to the base model

The focus of this article 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 cost as for the vessel owner cost. Therefore the following adjustments to the model where done.

Firstly, the model has been extended with functionality to allow the calculation of the vessel owner cost. This means that the total cost for operating a container vessel, on a given loop, can be calculated. These costs include all the vessel related cost 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)[2] containing the distance sailed in ECA zones. This means that for each port-to-port combination, in the total maritime distance database in the model[3], this additional information is added. 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 speed of the vessel and by the distance sailing in the ECA zones. The fuel consumption of the vessel, using different measures to mitigate the ECA-regulations is then determined by the following formula.

$$FC_{Voyage,i} = FC_{ECA,i} + FC_{NONECA,i} \quad (1)$$

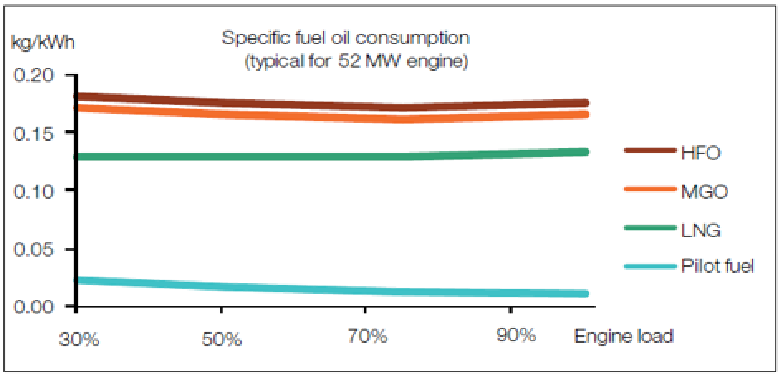
In which $FC_{Voyage,\,i}$ is the fuel cost for a voyage for vessel type i[4], while $FC_{ECA,\,i}$ and $FC_{NONECA,\,i}$ are the fuel cost for a voyage in either the ECA zones or a non-ECA zones.

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

[1] For a more detailed description of the model, reference is made to van Hassel et al. (2016) and van Hassel et al. (2018).
[2] https://www.marinetraffic.com/nl/voyage-planner/.
[3] The maritime distance database is a 80 by 80 matrix.
[4] In the model 20 different container vessel sizes are included, ranging from 500 TEU load capacity up to 20.000 TEU. The vessel data is collected from RINA (1991 – 2016).

In this formula D_{ECA} is the distance sailed in the ECA zones (nm), $V_{Vessel,\,i}$ is the speed of vessel type i, $SFC_{i,j}$ is the specific fuel consumption of the considered engine type or installation j (LNG, MDO or scrubbers) for vessel type i (tonnes/h). The deltas represent the displacement of the vessel, both for the payload as for the lightweight and are both expressed in cubic meters. Pb_i is the installed engine power in kW and $C_{Admin,\,i}$ is the admiralty constant of vessel type i (kW/ (kn^3.tonne$^{/3)}$). By including these elements in the model, it is possible to also research the effects of operational speed changes. FP_j is the fuel price per tonne 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 which is not in the ECA zones (nm). By adding the above-mentioned formula, the model needs some data to be able to quantify the fuel consumption. In order to calculate the fuel consumption of each vessel type, the following graph is used to consider the fuel consumption of HFO, LNG, and MGO.

Fig. 3. Specific fuel oil consumption



Source: (MAN Diesel and Turbo, 2011).

Based on figure 3, the fuel consumption for LNG engines is determined at and 0.15 kg/kWh. The LNG engine fuel consumption includes not only the direct fuel consumption of LNG but also the fuel consumption of the pilot fuel. Based on the installed power, along with the design speed of the vessel, the fuel consumption per hour can be determined. The design speed of the vessel and the needed power to sail at that speed (85% MCR) are taken from the data of RINA (1992-2016) for the different vessel types. For the fuel consumption of vessels sailing on MDO and HFO, the hourly fuel consumption at design speed is taken from RINA (1992-2016) for the different container vessels. An overview of the different fuel consumptions for container vessel ranging from 4.600 TEU to 18.800 TEU is reported in table 6.

Table 6. Fuel consumption of vessels for different fuels and scrubber technology

Vessel Size (TEU)	Installed Power (kw)	Fuel Consumption main engine (tons/hour)	Fuel Consumption auxiliary engine (tons/hour)	Fuel Consumption main engine (tons/hour)	Fuel Consumption main engine (tons/hour)	Fuel Consumption auxiliary engine (tons/hour)
		HFO/MDO		**LNG**	**Scrubber system Scenario***	
4600	36560	6.58	0.30	5.48	6.78	0.31
5466	24680	4.44	0.31	3.70	4.58	0.32
9115	41400	7.45	0.73	6.21	7.68	0.75
13892	62030	11.17	0.53	9.30	11.50	0.55
18800	61000	10.98	0.57	9.15	11.31	0.59

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

*In the model, a 3% increase in fuel consumption is considered for the scrubber system (The use of scrubbers increases the energy consumption, which is calculated to raise fuel consumption by 3% in the case of seawater scrubber and by 1% in the case of freshwater scrubber) (den Boer & Hoen, 2015).

Next to the adjustments to the fuel cost, also some cost impacts are expected in the running cost of the container vessels. These running costs include costs such as crew cost, repair, and maintenance cost, insurance cost and are given in van Hassel et al. (2016). According to Man diesel and Turbo (2011), with respect to the LNG scenario, crew cost, maintenance, and repair cost increase by 10% with respect to reference/base scenario (using MDO or HFO). While for the scrubber scenario, crew cost, maintenance, and repair cost raise by 20% respect to the reference scenario. Moreover, the external costs of pollutants such as SO_x, NO_x, CO_2, and PM are considered.

The last cost element that requires some additional inputs are the capital costs. Also for these costs, the same data is used as in van Hassel et al. (2016). Only the cost must also include the installation of LNG propulsion (retrofit) or a scrubber system. The installation cost for LNG propulsion and scrubber system are reported in table 7.

Table 7. The investment cost for LNG propulsion and scrubber system of ship types - Source: Own composition based on Aronietis et al., (2015)

Vessel Size	Average investment cost [Euro]	Lifetime [Year]	Investment cost [Euro per year]	Average investment cost [Euro]	Lifetime [Year]	Investment cost [Euro per year]
		LNG Propulsion			**Scrubber system**	
4,600 TEU	15,000,000	27	555,556	2,500,000	10	250,000
5,466 TEU	15,000,000	27	555,556	2,500,000	10	250,000
9,115 TEU	17,000,000	27	629,630	2,500,000	10	250,000
13,892 TEU	19,000,000	27	703,704	3,000,000	10	300,000
18,800 TEU	20,000,000	27	740,741	3,000,000	10	300,000

The average investment cost varies based on the ship type and vessel size. The lifetime of the LNG system is 27 years, while for the scrubber system, it is considered 10 years (Aronietis et al., (2015)). Moreover, the yearly investment cost for LNG propulsion is obtained by dividing the average investment cost by the total lifetime (27 years), while for scrubber technology, the average investment cost is divided by 10 years to acquire the yearly investment cost.

4. Scenario development

In this research different scenarios will be developed. Firstly, there is the reference scenario. This reference scenario simulates the "business as usual" situation with the aim of providing a comparison reference for the modeled alternative scenarios. In the reference scenario, the vessel complies with the ECA zones regulation by means of using MDO fuel. Outside the ECA zones, the vessel will use HFO.

The alternative scenarios tested are those selected in section 2. Every scenario is a combination of input data that characterizes the investigated technology. These include associated investment costs and fuel cost impacts. There two alternative scenarios tested in this research are the LNG scenario and the scrubber system scenario. The main differences of the scenarios are dependent on the types of engine and fuel used inside ECA and outside ECA zones. The features of each scenario are reported in table 8.

Table 8. Different scenarios based on the type of engine

Scenario	Engine	Fuel used inside ECA	Fuel used outside ECA
Reference scenario	Diesel Engine	Marine Diesel Oil (MDO)	Heavy Fuel Oil (HFO)
LNG scenario	LNG Engine	LNG	LNG
Scrubber system	Diesel Engine	Heavy Fuel Oil (HFO)	Heavy Fuel Oil (HFO)

In this research, the different scenarios are tested for two different routes. The first one is a route from Asia to Europe and the second from the US to Europe. For each route, different container vessel sizes are tested. An overview is given in table 9.

Table 9. Ports in the loop of each route[5]

Loop	Ports in the loop	Vessel sizes
Asia-Europe	Ningbo - Shanghai – Xiamen - Hong Kong – Yantian - Port Kelang - Tanger Med – Southampton – Hamburg – Bremerhafen – Zeebrugge – Rotterdam - Le Havre – Marsaxlokk - Khor al Fakkan - Jebel Ali - Ningbo	9115 TEU 13892 TEU 18800 TEU
US-Europe	Miami - Jacksonville – Savannah – Charleston - New York – Antwerpen – Bremerhafen- Rotterdam - Le Havre - New York – Norfolk – Charleston - Miami	4600 TEU 5466 TEU 9115 TEU

Besides the different vessel sizes also different vessel speeds are analyzed. This means that, for each size of vessel and each scenario, three different speeds (percentage of design speed of the vessel size (90%, 80%, and 70%)) are considered. With respect to the fuel cost, these costs are collected from Bunkerworld (2018) and are 400 EUR/tonne for HFO, 494 EUR/tonne for MDO and 310 EUR/tonne for LNG. The external cost are taken from External Costs of Transport in Europe (2011) and the value for SO_x is 0.04 EUR/tonne, for NO_x is 1328 EUR/tonne, for particulate matter (PM10) is 0.48 EUR/tonne and for CO_2 is 25 EUR/tonne. In order to assess the impact of the considered options from a maritime supply chain point of view, first, a supply chain must be determined. The considered supply chains in the scenarios are given in table 10.

Table 10. Considered supply chains

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

[5] These routes are based on existing container loops from CMA-CGM.

5. Scenario analysis and empirical results

The adjusted chain cost model will be applied for the above-mentioned scenarios. For each scenario, both the maritime cost from a shipowner point of view and for the chain cost is calculated. Firstly, the results of the maritime cost for the Asia – Europe route are discussed, while in section 5.2 the results for the container loop from the US to Europe are given.

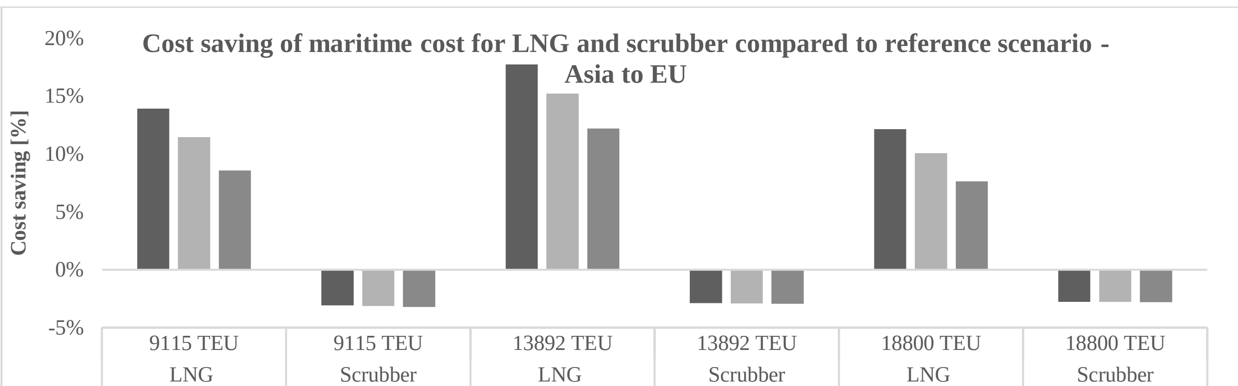
5.1. Asia to Europe route

Each researched route is divided into two subsections. In the first one, the results with respect to the vessel owner cost are given, while in the second section the results for the supply chain impact are reported.

5.1.1. Vessel owner cost

For Asia to Europe loop, the cost differential for the two alternative scenarios compared to references scenario is given. For each scenario, the different vessel types are considered as well as three different speeds (percentage of design speed such as 90%, 80%, and 70%). The results are given in Figure 4.

Fig. 4. Comparison of cost saving of scenarios (vessel owner)



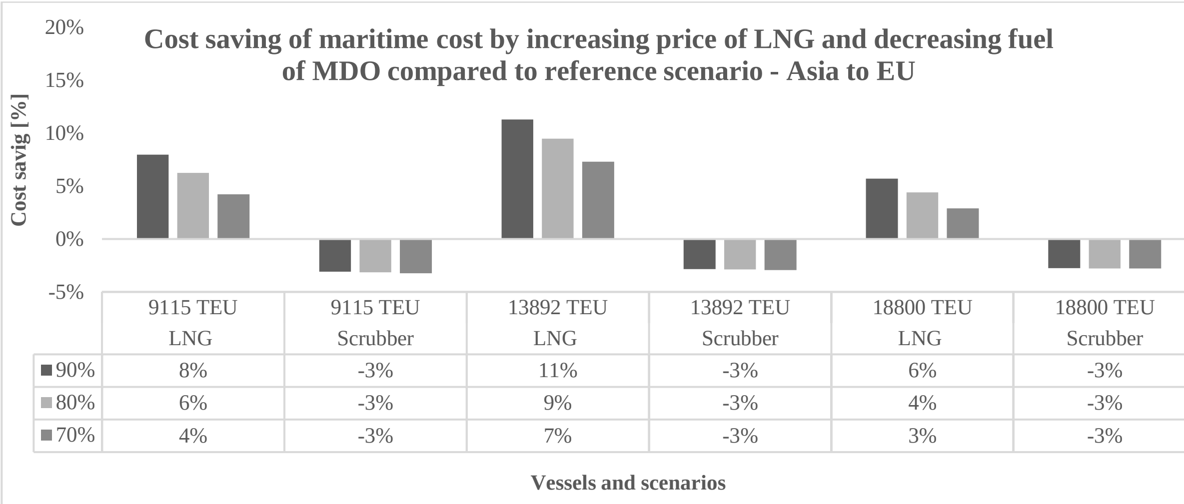
	9115 TEU LNG	9115 TEU Scrubber	13892 TEU LNG	13892 TEU Scrubber	18800 TEU LNG	18800 TEU Scrubber
90%	14%	-3%	18%	-3%	12%	-3%
80%	11%	-3%	15%	-3%	10%	-3%
70%	9%	-3%	12%	-3%	8%	-3%

Figure 4 shows that for the Asia –EU loop, the most economical alternative technology would be the LNG system since it has the highest cost saving with respect to other scenarios. However, for vessel 18800 TEU, the maritime cost increases significantly, which leads to the reduction of cost-saving respect to other two vessel types. It should be mentioned that, for all the three scenarios and by speed reduction, maritime cost decreases as well which means that the cost-saving increases. The reason is that speed reduction leads to a decrease in fuel consumption, which reduces the maritime cost.

Besides the variation of speeds, also the results obtained from the scenarios are compared by changing the price of MDO and LNG. The aim of this part is to figure out how the maritime and chain costs are affected by changing the price of fuel. To do so, the fuel cost of MDO is decreased to 425 [Euro/ton] which is a 13% reduction compared to base fuel price, while, the fuel cost of LNG is increased by 18% and reaches to 380 [Euro/ton]. Moreover, all the other parameters are kept as the first part of the methodology and the model is run to recalculate the maritime and chain costs for two maritime routes and for all sizes of vessels.

Figure 5 depicts the cost saving of alternative solutions with respect to the base scenario.

Fig. 5. Comparison of cost savings of scenarios (other fuel cost values)



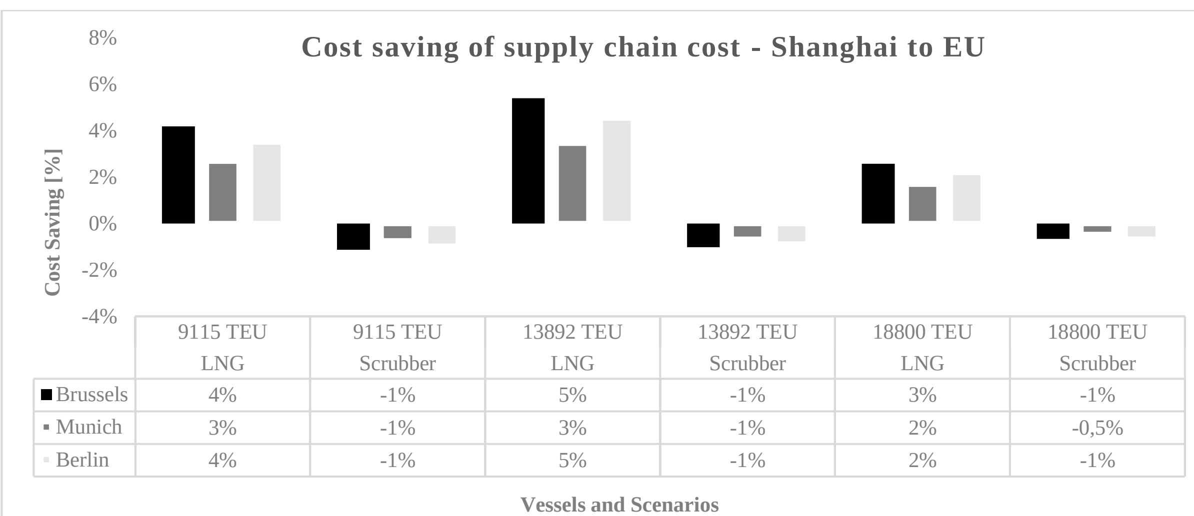
	9115 TEU LNG	9115 TEU Scrubber	13892 TEU LNG	13892 TEU Scrubber	18800 TEU LNG	18800 TEU Scrubber
90%	8%	-3%	11%	-3%	6%	-3%
80%	6%	-3%	9%	-3%	4%	-3%
70%	4%	-3%	7%	-3%	3%	-3%

By changing the fuel price of LNG and MDO and comparing figures 4 and 5, some new results are achieved. On Asia – Europe route and by comparing three scenarios, it is obtained that for both the base and scrubber scenarios, the maritime cost decreases gradually with respect to the base fuel price situation (increasing the cost saving), while in the LNG scenario, this cost increases which shows the decrease in cost saving. Similar to the base fuel price situation, the LNG system remains the cheapest and the cost saving of this system is higher than the scrubber scenario. It should be noticed that fuel price does affect the maritime cost significantly and by increasing the fuel price of LNG, the cost saving is reduced compared to the base fuel price situation.

5.1.2. Supply chain cost impact

The results of the generalized supply chain cost are reported in figure 6.

Fig. 6. Generalized cost on the Asia – Europe route

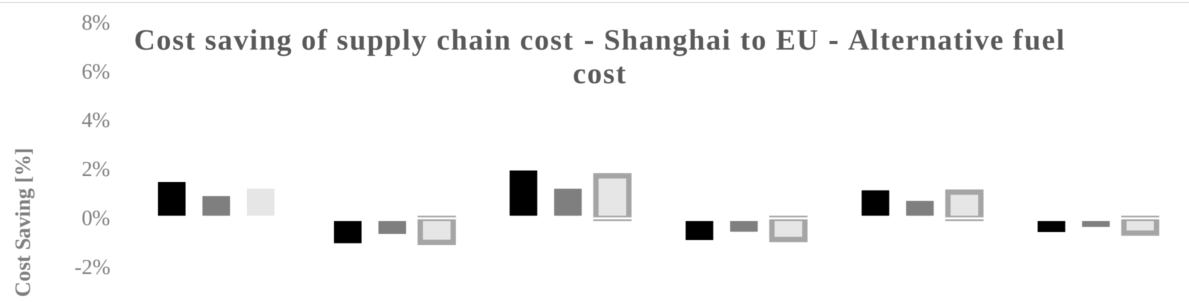


	9115 TEU LNG	9115 TEU Scrubber	13892 TEU LNG	13892 TEU Scrubber	18800 TEU LNG	18800 TEU Scrubber
Brussels	4%	-1%	5%	-1%	3%	-1%
Munich	3%	-1%	3%	-1%	2%	-0,5%
Berlin	4%	-1%	5%	-1%	2%	-1%

By comparing the generalized cost obtained for each city, it can be observed that cost saving is dependent on the distance to the port. On route from Asia to Brussels, most of the cost is made up of maritime cost because the hinterland cost is relatively low which states the largest cost saving is for Brussels compared to other cities. However, by transhipment from Asia to Munich or Berlin, the hinterland distances are longer and consequently the hinterland cost in larger. Therefore, the maritime cost contribution to the overall cost is dependent on hinterland distance.

Moreover, based on figures 4 and 6 and by comparing the cost saving of LNG scenario at 90% of speed, it can be observed that the effect of using alternative fuel technology is higher for shipowner rather than cargo owner. As can be seen and as an example for vessel 9115 TEU, the cost saving from shipowner point of view is 14% while from chain cost perspective this impact reduces to 4%. In 13892 TEU, the cost saving drops from 18% to around 5%. In other words, the impacts are relatively high for cost saving from shipowner point of view for LNG propulsion, but from a supply chain perspective, this effect is lower. The results of the alternative fuel cost are given in figure 7.

Fig. 7. Generalized cost on the Asia – Europe route (alternative fuel cost)



	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%

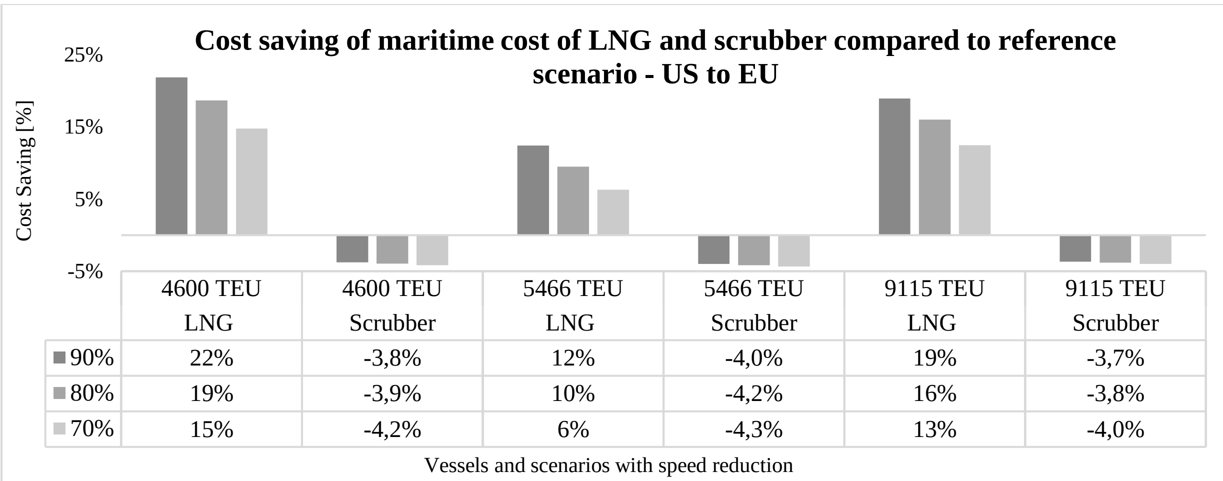
By comparing the figures 6 and 7, it can be observed that fuel price affects the generalized cost as well. Since the LNG cost increases, the generalized cost grows as well and it leads to a reduction of cost saving of LNG compared to the base fuel price situation. However, for scrubber technology, cost saving remains unchained compared to base fuel price (a small change in cost saving). For both base and alternative fuel prices, the LNG propulsion has higher cost saving and reflects better economical option compared to scrubber technology. However, this ratio is not significant and is about 5% at the maximum level for ship type 13892 TEU.

5.2. US to Europe route

5.2.1. Vessel owner cost

On this route, different ship types are selected. The results of maritime costs are reported individually for each scenario based for different speeds. The cost savings of different technologies are reported in figure 8.

Fig. 8. Comparison of cost saving of scenarios

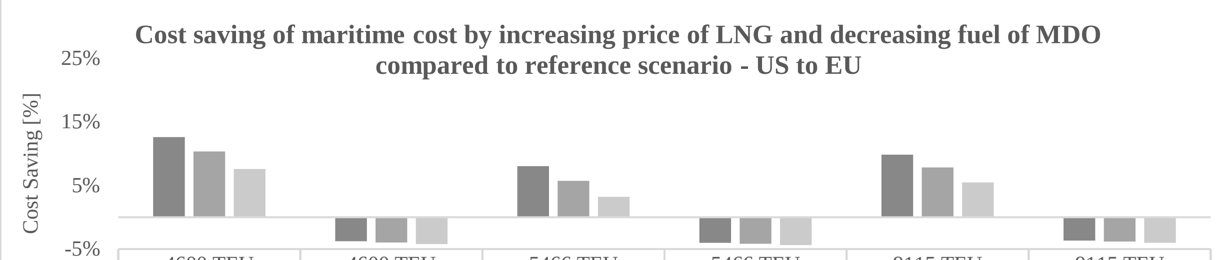


	4600 TEU LNG	4600 TEU Scrubber	5466 TEU LNG	5466 TEU Scrubber	9115 TEU LNG	9115 TEU Scrubber
90%	22%	-3,8%	12%	-4,0%	19%	-3,7%
80%	19%	-3,9%	10%	-4,2%	16%	-3,8%
70%	15%	-4,2%	6%	-4,3%	13%	-4,0%

As can be seen in this case, for all the vessels, there is a positive cost saving of the LNG propulsion, which states the lowest maritime cost compared to other options. As it is shown, the scrubber system is the most expensive option, however, this value is not significant by representing only 4% compared to the reference scenario.

As the size of vessel increases, the maritime cost increases as well, however, since for the vessel 5466 TEU, the installed power of propulsion parameter is lower than 4600 TEU, therefore, the maritime cost for this vessel is lower than the other two (because fuel consumption is derived from installed power and as it is lower, it does affect the maritime cost). In figure 9 the results of the alternative fuel cost scenarios are given.

Fig. 9. Comparison of cost savings of scenarios (alternative fuel cost).



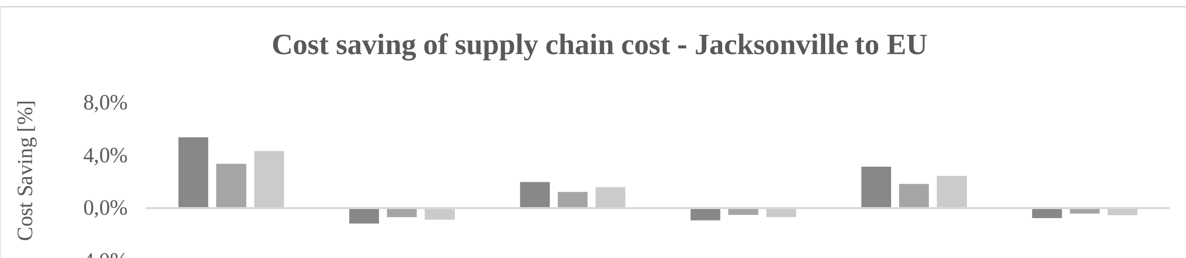
	4600 TEU LNG	4600 TEU Scrubber	5466 TEU LNG	5466 TEU Scrubber	9115 TEU LNG	9115 TEU Scrubber
90%	13%	-3,8%	8%	-4,0%	10%	-3,7%
80%	10%	-4,0%	6%	-4,2%	8%	-3,8%
70%	8%	-4,2%	3%	-4,4%	5%	-4,0%

On this route, by comparing figure 8 and 9, the findings for the US – Europe route are that the maritime cost reduces gradually for both base and scrubber scenarios. However, for the LNG system, the maritime cost increases for all vessel sizes, which leads to the reduction of the cost saving of the LNG system with respect to the base fuel price situation. For example, for ship type 4600 TEU and for 90% of speed, the cost saving diminishes from 22% to 13% by changing the price of LNG. This fact is valid for ship types 5466 TEU and 9115 TEU by decreasing the cost saving from 12% to 8% and from 19% to 10% respectively. Therefore, it can be concluded that, by changing the fuel price, the LNG becomes a less economic option but still has the highest cost saving compared to the scrubber system and is considered as the cheapest fuel alternative. In addition, the cost saving of the scrubber scenario is negative for all the vessels, which means that it is a more expensive option with respect to the reference and LNG scenarios. Moreover, by increasing the fuel price of MDO, the effect is not significant by comparing scrubber technology with the reference situation, which shows the same amount of cost saving with respect to base fuel price.

5.2.2. Supply chain cost

With respect to the generalized supply chain cost, the results of the analysis are presented in figure 10.

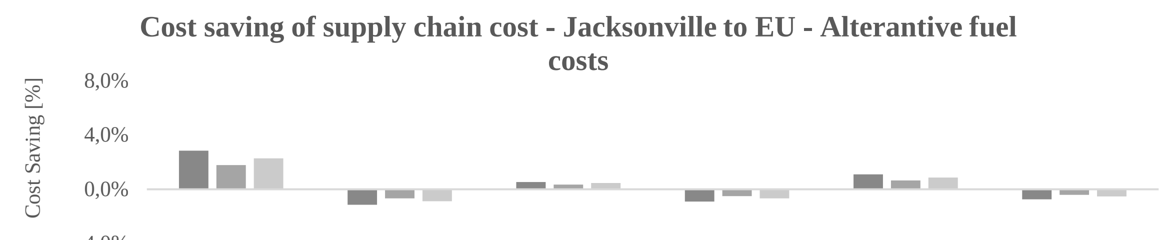
Fig. 10. Generalized cost on the US – Europe route



	4600 TEU LNG	4600 TEU Scrubber	5466 TEU LNG	5466 TEU Scrubber	9115 TEU LNG	9115 TEU Scrubber
Brussels	5,4%	-1,17%	2,0%	-0,92%	3,1%	-0,75%
Munich	3,3%	-0,69%	1,2%	-0,52%	1,8%	-0,41%
Berlin	4,3%	-0,89%	1,6%	-0,68%	2,4%	-0,54%

Figure 11 gives the results of the maritime supply chain cost for alternative fuel cost.

Fig. 11. Generalized cost in the US – Europe route (alternative fuel costs)



	4600 TEU LNG	4600 TEU Scrubber	5466 TEU LNG	5466 TEU Scrubber	9115 TEU LNG	9115 TEU Scrubber
Brussels	2,9%	-1,2%	0,5%	-0,9%	1,1%	-0,7%
Munich	1,8%	-0,7%	0,4%	-0,5%	0,6%	-0,4%
Berlin	2,3%	-0,9%	0,5%	-0,7%	0,9%	-0,5%

Vessels and Scenarios

By comparing the above graphs, it can be observed the effect of fuel price on supply chain cost. By increasing the fuel price of LNG, the cost saving of this alternative option decreases compared to the base fuel cost situation. However, the cost saving of the scrubber system remains unchanged. By increasing the fuel price of LNG, although the cost saving of this option reduces, however, it is still a better economic option by presenting the lowest generalized cost.

By comparing the obtained cost savings from figures 8 and 10, it is observed that the impact of maritime cost is higher for shipowner rather than supply chain perspectives for LNG propulsion. For vessel 4600 TEU and 90% of speed, this value drops from 22% to around 5%. For vessel 5466 TEU, the cost saving for shipowner is 12% while cost saving from supply chain perspective is only 2% and for vessel 9115 TEU, the cost saving reduces from 19% to 3% which is a significant value.

6. Conclusion

International maritime shipping has been affected by new regulations in order to reduce the pollutants emitted from vessels globally and in the ECA zones in a more strict way. In order to respect the legislation, there are some alternative options for shipowners such as LNG propulsion, MDO, and scrubber technology. In this research, the mentioned alternative solutions are assessed economically not only from shipowner point of view but more important, from a shipper point of view by evaluation of generalized chain cost. The latter assessment shows how alternative options will affect the generalized cost and which option will provide the lowest generalized cost, which affects the policymaking process and provides a great view for logistic operators in order to deploy the best alternative solution.

This research intends to overcome two research objectives, namely the evaluation of maritime cost first and second the assessment of chain cost of some types of containerships for three alternative fuel options, being LNG, MDO and scrubber technology. For this aim, the ‘Chain Cost Model’ is used. The idea is to compare the obtained results for different fuel technologies and to figure out which option would be the best from an economic point of view. The fuel alternative technologies such as LNG propulsion and scrubber system have been compared economically to a reference case using MDO within the ECA zones and for some ship, types trading between Europe, US, and China. The economic comparison is made with three different scenarios of engine types and the fuel used inside and outside the ECA zones. Moreover, in the second part of the approach, this comparison has been put forward by using two different levels of fuel prices by increasing the fuel price of LNG by 70 [euro/ton] and decreasing the price of MDO by 80 [euro/ton] to realize the effect of fuel price on the maritime and chain costs. In this model, the external costs of pollutants such as SO_x, NO_x, CO_2, and PM are considered.

Based on the performed analysis it is found that: first, the LNG system has the lowest maritime cost compared to the reference and scrubber scenarios for both Asia and the US to EU routes. Second, the cost saving of the LNG scenario is higher than scrubber scenario respect to the reference scenario, while the cost saving of the scrubber scenario is negative for all the vessels for both shipowner maritime cost and supply chain cost. The results show that, for both Asia-EU and US-EU routes, LNG propulsion is the best economical option by demonstrating the lowest maritime and generalized cost compared to scrubber technology and reference scenario. Thirdly, by comparing the maritime cost of the vessels for all three scenarios and both routes, it is observed that as the percentage of design speed is decreasing, the cost of maritime transport decreases as well; moreover, this reduction is significant as the size of the vessel increases. Besides, the maritime cost increases as the size of the vessel increases.

By comparing the obtained results, it can be concluded that the supply chain impact depends not only on ship size but more significant on the maritime distance. It can be interpreted that, in a longer maritime distance from Asia to Europe, the maritime cost is relatively higher compared to shorter maritime distance from the US to Europe and in this case, the majority of costs are related to hinterland costs.

By 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-saving reduces significantly compared to base fuel price. The reason is that maritime cost of LNG increases significantly by increasing the fuel price of LNG and at the same time, the maritime cost of reference scenario decreases by decreasing the fuel price of MDO, which leads to the reduction of cost saving of LNG propulsion. Moreover, the cost saving of scrubber scenario with respect to a reference scenario does change slowly. Therefore, it can be concluded that, by changing the fuel price, the LNG becomes a less economic option but still has the highest cost saving compared to the scrubber system and is considered as the most economical fuel alternative.

It is worthwhile to mention that, by comparing the alternative fuel cost with base fuel price situation, it is found that, the maritime cost is influenced by the price of fuel in which for LNG propulsion this influence is much higher and more significant. Moreover, the effect of using alternative fuel technology is higher for shipowner rather than the cargo owner. In other words, the impacts are relatively high for cost saving from shipowner point of view for LNG propulsion, but from a supply chain perspective, this effect is lower. This fact reveals that the price of fuel plays an important role in order to choose an alternative fuel option, besides that, other features such as installation cost, crew, and maintenance cost are other significant factors.

The obtained results are worthwhile for both logistics operators (shipping companies, shippers, freight forwarders, etc.) and policymakers. For logistics operators, the findings are relevant, as they allow making the economically most rewarding investments, taking into account potential internalization of external costs. For governments, it is important to know which solution gives the best socio-economic cost returns. In order to extend the research objectives regarding this topic, further research can be done including other types of vessels such as bulk carriers, Ro-Ro vessels, etc. Moreover, other maritime routes might be considered such as South America to the EU.

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