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The impact of sulphur limit fuel regulations on maritime supply chain network design

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Abstract
Although the greening of the marine sector started over a decade ago, the emissions produced from ships and port operating equipment have been only recently perceived as issues to be addressed. On this basis, the International Maritime Organisation (IMO) decided to enact stricter sulphur limits on the fuel oil used by ships in Sulphur Oxide (SOx) Emission Control Areas in an effort to reduce the environmental impact of the vessel's bunkers. In this respect, the purpose of the paper is to quantify the cost implications of the IMO revised regulations on the shippers' traditional supply chain network design decisions through the development of a strategic Mixed Integer Linear Programming decision-support model. The applicability of the model is demonstrated on a realistic maritime supply chain operating within the East Asia—EU trade route. The results reveal that the implementation of the sulphur limits at the route's ports may not affect the shippers' network structure under the current fuel prices, as the optimally selected ports have cost effective hinterland transportation connections within the EU market, that make them preferable for the shipper, even though the network's shipping costs increase.

Keywords Sulphur Limits · Shipper · Carrier

1 Introduction

Green supply chain management emerged as a response to the introduction of the different environmental awareness regulations in 1990 s (Wu and Dunn 1995). As a result, companies started to implement green practices in their supply chain networks to ensure compliance with

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regulations and increased profitability. The greening of the supply chain networks could be achieved through reduction of CO_2 emissions and thus reduction of Greenhouse Gas (GHG) emissions, waste reduction and treatment, resource efficiency, usage of alternative/ more environmentally friendly fuels (Chhabra et al. 2017). Although green supply chain network policies have been in place for many years, the transportation of global supply chains still accounts for a significant percentage of the global GHG and CO_2 emissions.

In particular, shipping contributes to the largest portion of globalized supply chain emissions, causing approximately 2.5% of the global GHG emissions (IMO 2015). As the world seaborne trade is expected to increase by 2.8% in 2018, with total volumes reaching 10.6 billion tons (UNCTAD 2017), the effective management of its emissions could lead to significant improvements in the environmental performance of globalized supply chains. On this basis, in January 2015 the International Maritime Organization (IMO) set stricter requirements for sulphur limits on the fuel oil used by ships in SOx Emission Control Areas (ECAs). These additional limits were reduced from a 3.5% m/m (mass by mass) to a 0.1% m/m limit (IMO 2016). The ECAs established under MARPOL Annex VI for SOx are the Baltic Sea area, the North Sea area, the North American area (covering designated coastal areas off the United States and Canada), and the United States Caribbean Sea area (around Puerto Rico and the United States Virgin Islands). Moreover, a global limit for sulphur in fuel oil is set in all shipping routes to 0.5% m/m and will be applied from the 1st of January 2020.

There are three options available for ship operators to comply with the revised IMO regulations, namely: (1) the use of low-sulphur compliant fuel oil; (2) the use of methanol; and (3) the use of approved equivalent methods, such as exhaust gas cleaning systems or “scrubbers” (IMO 2016). However, the cost of implementation, the complexity, and the future fuel prices raise concerns regarding the implementation of these options, with Shi (2016) stating that the market based measures imposed by the IMO need to be further assessed for their effectiveness.

Another critical issue that arises through the additional SOx limits imposed by the IMO, involves the assessment of the implications of the revised IMO regulations on supply chain stakeholders, which are yet to be ascertained. The revised IMO regulations could lead to different supply chain structures (Sys et al. 2016). Additional research is needed for assessing the impact of the emission regulations from the supply chain network perspective (Lam and Gu 2013; Fahimnia et al. 2015). Under this context, the purpose of this paper is to quantify the impact of the SOx limits in the ECAs as of the 1st of January 2015, and in all trading routes as well as in the ECAs as of the 1st of January 2020, on maritime supply chain network design decisions.

The rest of the paper is organized as follows. Section 2 provides a review of literature on research efforts that consider maritime regulations. In Sect. 3 the system description is presented. Next, in Sects. 4 and 5 the model development process and the case study are discussed. Then, the numerical results of this study are presented in Sect. 6. The paper concludes with conclusions and avenues for future research.

2 Literature review

There is an interesting on-going research that deals with the evaluation of the impact of the different maritime emission reduction policies using a wide range of technical and methodological approaches. More specifically, Abadie et al. (2017) focused on the impact of the technical solutions related to IMO emission regulations compliance and considered the future fuel implications when choosing between fuel switching and installing a scrubber.

The stochastic model that was developed is based on fuel spot and future prices, cost for implementing the scrubbers, and the time that the vessel operates in an ECA and thus does not consider the real IMO regulations. The effectiveness and the costs associated with the speed of as a way to reduce $C0_2$ emissions has been also considered in previous studies as a way to comply with the emission regulations (Corbett et al. 2009). However, this study only considers the speed reduction aspect and does not consider the regulatory implications in the ECAs. Sys et al. (2016) examined the potential effects of the upcoming international maritime emission regulations on the competition between seaports and the potential underlying economic motivations related to the introduction of the ECAs. The latter study is based on secondary data and on stakeholders' views for future predictions of the impacts and does not consider the real IMO regulations.

Cariou and Cheaitou (2012) compared the effectiveness of the European speed limit regulations versus an international bunker levy related to CO_2 emissions reduction as these will be imposed by IMO. Their study considers only the speed and the fleet size and does not consider the IMO regulatory compliance costs. Similarly, Cheaitou and Cariou (2018) proposed a multi-objective optimisation model for profit maximization, CO_2 emissions minimization, and SOx emissions minimization considering the real IMO regulations with a focus on speed. Their analysis considers the case of demand sensitivity related to speed/transit time, but it does not consider the impacts on port operations and shippers' inventory costs. The technical and economic implications of the alternative fuel choices such as marine gas oil as well as the new engine technologies have been also examined in the literature (Armellini et al. 2018). This study considered the real IMO regulations to evaluate the different possible engine configurations using marine gas oil, which can be adopted on board a large cruise ship in order to identify the best compromise-solutions for environmental pollution, energy consumption, and space occupation. The focus of the latter study was on the economic and technical implications of technology related to the revised emission regulations on a sole tourist cruise rather than the supply chain network, which is the focus on the current study.

Becoming greener may come at the cost of being economic inefficient (Wu and Pagell 2011). Psaraftis and Kontovas (2010) found that there can be significant environmental and economic trade-offs among the different emission reduction policies in the maritime industry. It was suggested that the environmental targets may be achieved at the expense of the economic targets of the stakeholders. Hermeling et al. (2015) using a profit maximizing equation found that it is not possible to achieve emissions reduction based on the European emission-trading scheme in a cost-efficient manner. Although cost minimisation is the main objective of supply chain network design, global supply chains with increased transportation volumes and thus significant negative environmental implications will incur higher costs.

Wang et al. (2015) examined the possible implications of future alternative emission trading schemes on international shipping and suggested that any proposed mechanism should be assessed for its consequences from the supply chain network perspective. Different studies focused on the importance of reducing emissions in the marine and port logistics, however there is a need for more holistic and proactive approaches from a supply chain network perspective (Fahimnia et al. 2015). Sys et al. (2016) suggested that under the upcoming emission reduction regulations liner companies should be persuaded to change their routes in favour of Mediterranean ports. Thus, it is suggested that currently utilised supply chain networks may become inefficient due to the changes in maritime emission regulations. Since the implementation of these maritime emission regulations may affect the supply chain structure, it may as well have an impact on the decision of the entry port that supply chain stakeholders may select for supplying their demand points.

Numerous researchers strived to additionally evaluate the impact of these regulatory interventions on classical strategic network design decisions. On this basis, Fagerholt et al. (2010) and Lam (2010) developed decision support tools in response to the regulatory changes in the maritime sector which are focused on operational and cost indicators without considering the emission regulations element. Previous studies developed decision support tools to analyse fuel consumption and GHG emissions, environmental impact of port operation activities, and liner shipping network design problem to minimize the cost and emissions (Ballou et al. 2008; Bruzzone et al. 2010; Windeck and Stadtler 2011). However, the latter studies failed to consider the real IMO regulations. Other researchers considered hypothetical scenarios of other regulatory changes in the maritime emissions (Koesler et al. 2015; Kujanpää and Teir 2017; Sheng et al. 2017; Wen et al. 2017). Mallidis et al. (2012) developed a decision support model that considers CO_2 emissions cost parameters in supply chain network design. Although this study provides a comprehensive model for supply chain network design, the revised IMO regulations and their relative implications on supply chain network design need to be considered as well. There is a need for further research in the area of decision support systems in sustainable maritime transport area in relation to the increased regulations on GHG emissions by EU and IMO (Mansouri et al. 2015; Davarzani et al. 2016). Also, Christiansen et al. (2013) highlighted the need for research that identifies the proper network design, allocation of vessels to lines and the relative economic impact. Models that explicitly incorporate the emissions dimension referred as Green Ship Routing and Scheduling Problems are missing from the literature (Kontovas 2014).

A critical taxonomy of the literature review leads to the following Table 1 which presents papers considering none emission regulations, IMO regulations, other regulatory changes related to emissions in the marine sector, hypothetical regulatory changes, and real regulatory changes.

The results clearly demonstrate a lack of papers that deal with real IMO regulatory guidelines from the supply chain network perspective. Ship operators are required to reduce their environmental impact through different options available to become greener. However, the cost of implementation, the complexity, and the future fuel prices raise concerns about the latter options. The exact implications of the revised IMO regulations on supply chain stakeholders are yet to be ascertained. The latter changes in IMO's regulations in relation to current supply chain networks will need to be re-examined for their economic efficiency. The IMO regulations could affect the shippers' different supply chain structures. This in turn will affect the transportation mode selection decisions and decisions on the number of operating Distribution Centres (DCs). On this basis this paper contributes to the existing literature with a quantitative estimation of the impact of these regulatory guidelines on supply chain network design. The novelty of this paper is that the modelling is based on real-world costing practises associated to the revised IMO guidelines. Supply chain stakeholders could utilise the results of this study when designing their supply chain networks.

3 System under study

We consider a shipper's multi-echelon supply chain network that supplies various demand points in a region with a specific product. We assume that the required products are transported in containers from one distant loading port to a number of entry ports through deep-sea shipping, and then by alterative hinterland transportation modes such as heavy-duty trucks, rail and barge, to the central DCs. Finally, the transportation from the DCs to the demand

Table 1 Critical taxonomy of research efforts

References	No emission regulations	IMO regulations	Other regulations	Hypothetical regulatory changes	Real regulatory guidelines
Armellini et al. (2018)		x			x
Abadie et al. (2017)		x		x	
Ballou et al. (2008)	x				
Bruzzone et al. (2010)			x	x	
Cariou and Cheaitou (2012)			x	x	
Cariou and Cheaitou (2012)		x			x
Corbett et al. (2009)		x	x	x	
Fagerholt et al. (2010)			x	x	
Hermeling et al. (2015)		x	x	x	
Koesler et al. (2015)		x		x	
Kujanpää and Teir (2017)			x	x	
Lam (2010)	x				
Mallidis et al. (2012)		x		x	
Mansouri et al. (2015)			x	x	
Psaraftis and Kontovas (2010)		x	x	x	
Sheng et al. (2017)			x	x	
Sys et al. (2016)		x		x	
Wang et al. (2015)		x	x	x	
Windeck and Stadtler (2011)			x	x	
Wang et al. (2015)		x	x	x	
Wen et al. (2017)			x	x	

points occurs by delivery truck transportation only. Figure 1 provides a simplified realization of the supply chain network under study, with one Loading Port (LP), two Entry Ports (EPs), two DCs and four Retail Stores (RSs).

We examine three options for the strategic design of the network as these are summarized in Table 2. In the first option i.e. Option A, no ECAs exist and thus all carriers use the conventional IFO 380 and 180 bunker fuels throughout the whole voyage. In Option B,

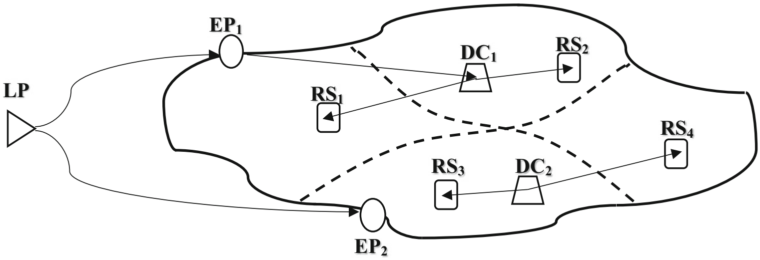


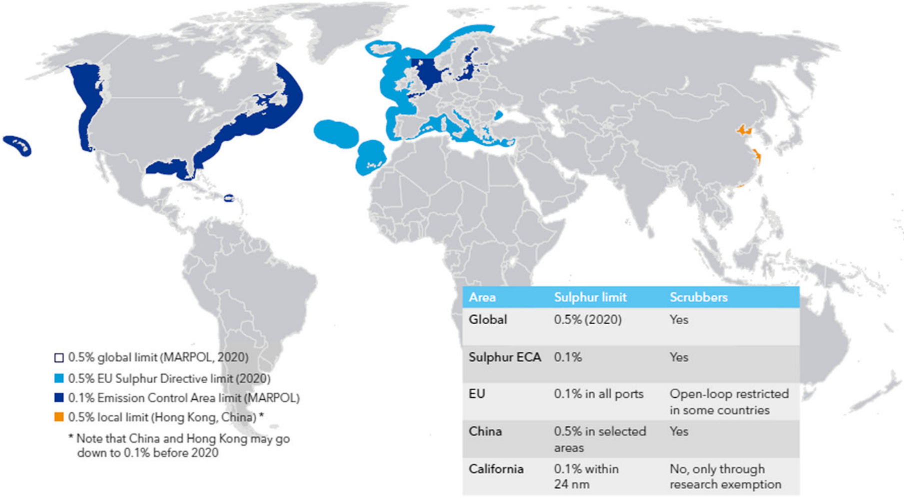
Fig. 1 Simplified realization of the network under study

Table 2 Maritime supply chain network options

Options	Description
A	No SOx Limit requirements
B	Stricter 0.1% m/m SOx limit requirements within the ECA areas
C	0.5% m/m SOx limit requirements in all trading routes, and 0.1% within the ECAs

which is currently active since 2015, all carriers use conventional IFO 380 and 180 bunker fuel until they reach the ECAs, and then they switch to the sulphur fuel oil that meets the 0.1% m/m limit requirements within the ECAs. Finally, Option C involves the IMO regulatory framework that will be enacted after 2020. The framework requires a 0.5% m/m SOx limit restriction to be imposed in all trading routes outside the ECAs and a 0.1% m/m SOx limit restriction in the ECAs. In the latter case the carriers will need to employ a fuel type which meets the 0.5% m/m SOx limits in all routes outside the ECAs, and then switch to a fuel type which meets the 0.1% m/m SOx limits. In Options B and C, more expensive fuel types are employed compared to the IFO 380 and 180 of Option A; thus, sea voyage costs increase for Option B and C. Assuming that the increased costs pass to the shipper, freight rates will also increase. Hence, it could be that the traditional coastal routes, which are predominantly in the Asia—US East Coast as well as in the Asia—North West Europe route, will be affected as the shippers may select closer to the loading port, EPs as starting points for the supply of their demand points. Figure 2 illustrates the current ECAs and non ECAs as these are designated under MARPOL Annex VI.

The decisions that should be made for the strategic design of the shipper's supply chain network are related to: (1) the selection of the Entry Ports; (2) the selection of the optimal location and capacities of the DCs; (3) the selection of the transportation mode employed



Area	Sulphur limit	Scrubbers
Global	0.5% (2020)	Yes
Sulphur ECA	0.1%	Yes
EU	0.1% in all ports	Open-loop restricted in some countries
China	0.5% in selected areas	Yes
California	0.1% within 24 nm	No, only through research exemption

Fig. 2 ECA areas under MARPOL Annex VI. (*Source*: MRV 2018)

between the Entry Ports and the DCs; and (4) the determination of the product flows between the nodes of the network under study.

The optimization criterions involve: (1) the transportation costs per TEU between the nodes of the network under study along with the higher cost that the carrier suffers for using the more expensive fuel that meets the 0.1% and 0.5% m/m SOx limit requirements; and (2) the DC operating and depreciation costs per time unit.

4 Model development

The model employed for the design of the supply chain network under study is formulated as a Mixed Integer Linear Programming Model (MILP). The supply chain originates from a distant loading port 0, onto a number of potential entry ports $i \in EP$ and then to a number of potential central distribution centre $j \in DC$ by alternative transportation modes $m \in M$. The distribution centres j then serves the shipper's demand points $r \in RS$ by delivery trucks.

In Option A as seen in Table 3, the supply chain cost parameters include: (i) the carrier's freight rate per TEU from the loading port 0 to the entry port i; (ii) the transportation cost per TEU for each mode from the entry point i, to the DC j; (iii) the delivery truck transportation cost per TEU from the DC j to the demand point r; and (iv) the DC operating and depreciation costs per time unit.

With respect to carrier's freight rates and as these change for each option as seen in Table 4, we consider the following three nomenclatures. In the first Option A, the carrier's freight rate per TEU from the loading port 0 to each Entry Point i, is denoted by c_{0i}^{IFO}. Specifically for each EP within the ECAs, c_{0i}^{IFO} is equal to the current freight rate minus the extra cost that the carrier suffers for using the more expensive 0.1% m/m SOx limit compliant fuel from the start point of the ECAs until the EP. In Option B, the freight rate per TEU to each EP i is the current one and is denoted by $c_{0i}^{0.1}$. Finally in Option C the freight per rate per TEU to each EP i is denoted by $c_{0i}^{0.5}$. In this case, the current freight rate to each EP outside the ECAs is now surcharged with the extra cost that the carrier suffers for currently using the more expensive 0.5% m/m SOx limit compliant fuel from the loading port to the EP, while for the EPs within the ECAs, the current freight rates to each ECA port is surcharged with the extra cost of the more expensive 0.5% m/m SOx limit compliant fuel used from the loading port to the start point of the ECA.

Table 3 Nomenclature of the model's decision variables

Parameters	Description
$x_{0\iota}^{IFO}, x_{0\iota}^{0.1}, x_{0\iota}^{0.5}$	No of TEUs per time unit transported from the distant loading point 0 to the entry port i in Options A, B and C respectively.
x_{ij}^{m}	No of TEUs per time unit transported from the entry port i to DC j (TEUs/time unit)
x_{jr}	No of TEUs per time unit transported from the DC j to the demand point r (TEUs/time unit)

Table 4 Nomenclature of the model's Parameters

Parameters	Description
$c_{0\iota}^{IFO}, c_{0\iota}^{0.1}, c_{0\iota}^{0.5}$	Freight rate per TEU from the loading port 0 to the entry port *i* in Options A, B and C respectively
c_j	DC operating and depreciation cost per TEU per time unit
c_{ij}^m	Transportation cost per TEU from the entry port *i* to the DC *j* with the transportation mode m
c_{jr}	Delivery truck transportation cost per TEU from the DC *j* to the demand point *r*
Cap_j	Capacity level of each operating DC j (TEUs)
D_r	Known demand at demand point *r* (TEUs per time unit)

Consequently, the total supply chain costs per time unit for Options A, B, and C can be estimated by Eqs. (1), (2), and (3) respectively.

$$MinTC_A = \sum_{i \in EP} c_{0i}^{IFO} \cdot x_{0\iota}^{IFO} + \sum_{i \in EP} \sum_{j \in DC} \sum_{m \in M} c_{ij}^m \cdot x_{ij}^m + \sum_{j \in DC} c_j \cdot Cap_j + \sum_{j \in DC} \sum_{r \in RM} c_{jr} \cdot x_{jr} \tag{1}$$

$$MinTC_B = \sum_{i \in EP} c_{0i}^{0.1} \cdot x_{0\iota}^{0.1} + \sum_{i \in EP} \sum_{j \in DC} \sum_{m \in M} c_{ij}^m \cdot x_{ij}^m + \sum_{j \in DC} c_j \cdot Cap_j + \sum_{j \in DC} \sum_{r \in RM} c_{jr} \cdot x_{jr} \tag{2}$$

$$MinTC_C = \sum_{i \in EP} c_{0i}^{0.5} \cdot x_{0\iota}^{0.5} + \sum_{i \in EP} \sum_{j \in DC} \sum_{m \in M} c_{ij}^m \cdot x_{ij}^m + \sum_{j \in DC} c_j \cdot Cap_j + \sum_{j \in DC} \sum_{r \in RM} c_{jr} \cdot x_{jr} \tag{3}$$

Subject to:

Flow constraints_Option A

$$x_{0\iota}^{IFO} = \sum_{m \in M} \sum_{j \in DC} x_{ij}^m \quad \forall \boldsymbol{i} \in \boldsymbol{EP} \tag{4}$$

$$\sum_{m \in M} \sum_{i \in EP} x_{ij}^m = \sum_{r \in RM} x_{jr}, \quad \forall \boldsymbol{j} \in \boldsymbol{DC} \tag{5}$$

$$\sum_{j \in DC} x_{jr} = D_r \quad \forall \boldsymbol{r} \in \boldsymbol{RM} \tag{6}$$

Flow constraints_Option B

$$x_{0\iota}^{0.1} = \sum_{m \in M} \sum_{j \in DC} x_{ij}^m \quad \forall \boldsymbol{i} \in \boldsymbol{EP} \tag{7}$$

$$\sum_{m \in M} \sum_{i \in EP} x_{ij}^m = \sum_{r \in RM} x_{jr}, \quad \forall \boldsymbol{j} \in \boldsymbol{DC} \tag{8}$$

$$\sum_{j \in DC} x_{jr} = D_r \quad \forall \boldsymbol{r} \in \boldsymbol{RM} \tag{9}$$

Flow constraints_Option C

$$x_{0i}^{0.5} = \sum_{m\in M}\sum_{j\in DC} x_{ij}^{m} \quad \forall \boldsymbol{i} \in \boldsymbol{EP} \tag{10}$$

$$\sum_{m\in M}\sum_{i\in EP} x_{ij}^{m} = \sum_{r\in RM} x_{jr}, \quad \forall \boldsymbol{j} \in \boldsymbol{DC} \tag{11}$$

$$\sum_{j\in DC} x_{jr} = D_r \quad \forall \boldsymbol{r} \in \boldsymbol{RM} \tag{12}$$

Non Negativity Constraints

$$x_{0\iota}^{IFO}, x_{0\iota}^{O.1}, x_{0\iota}^{O.5}, x_{ij}^{m}, x_{jr,} > 0$$

Constraints 4–12 guarantee the balance of inbound and outbound flows for each EP, DC, and Regional Market respectively in all three options.

To this end, and in order to provide a realistic approximation of the DCs capacity, which should be able to handle peak demands, we need to estimate a safety stock capacity for each DC. Thus, we assume that each DC faces a stochastic normally distributed demand per time unit with a mean equal to $\sum_{m\in M}\sum_{i\in EP} x_{ij}^{m}, \forall j$ and a standard deviation of demand per time unit denoted by $\sqrt{\sum_{m\in M}\sum_{i\in EP}(\sigma_{ij}^{m})^2}, \forall j$.

Moreover, we assume that each DC employs a periodic review (*R, Sj*) inventory planning policy, where *R* represents the DC's, review period considered the same for all DCs, and *Sj* is each DC's up to *Sj* order quantity. We assume that all DCs have to satisfy a specific common Service Level Type I requirement $P\left(\sum_{m\in M}\sum_{i\in EP} X_{L_{oij}^{m}+R} < S_j\right) = \Phi(z) = a\%$, where $\sum_{m\in M}\sum_{i\in EP} X_{L_{oij}^{m}+R}$ represents the normally distributed stochastic demand that a DC j faces during the review period *R* and the lead time from the loading port 0 to the entry port i and on to the DC j with each mode m, L_{oij}^{m}.

Finally, and assuming a specific coefficient of variation (cv) of demand per time unit for each DC, $cv = \frac{\sqrt{\sum_{m\in M}\sum_{i\in EP}(\sigma_{ij}^{m})^2}}{\sum_{m\in M}\sum_{i\in EP} x_{ij}^{m}} = b$, the safety stock level of each DC can be then estimated by: $ss_j = b \cdot \sum_{m\in M}\sum_{i\in EP} x_{ij}^{m} \cdot \sqrt{L_{oij}^{m} + R} \cdot \Phi^{-1}(z)$ and the DC's capacity by $Cap_j = ss_j + \sum_{m\in M}\sum_{i\in EP} x_{ij}^{m} \cdot R, \forall j$ where $\sum_{m\in M}\sum_{i\in EP} x_{ij}^{m} \cdot R$ represents each DC's net stock level sufficient enough to handle peak demands.

5 Case study

We illustrate the applicability of the proposed methodology in the case of a shipper's supply chain that exports refrigerators from China to the EU with a planning horizon of one year. The demand at each retail store is estimated considering each region's historical demand data retrieved by Euromonitor (2016).

The loading point is the port of Shanghai, while the EPs are the ports of Hamburg, Marseille Trieste, Le Havre, Rotterdam, and Piraeus. From these EPs only Rotterdam and Hamburg are located in the North Sea ECA, while the rest are not in ECA. Regarding the potential DC locations, we consider those of Venlo, Paris, Frankfurt, Berlin, Prague, Warsaw, Athens, Milan, Budapest and Bucharest. These DCs serve the RSs of Eindhoven, Sofia, Prague, Copenhagen, Munich, Berlin, Hamburg, Frankfurt, Riga, and Athens with an annual average demand of 2112, 284, 948, 384, 1788, 1248, 1020, 2220, 264 and 372 40ft containers (FEUs) respectively and with an average refrigerator capacity of 1.14 m^3.

The transportation from Shanghai to the EPs occurs with a 8000 TEU mother vessel that exhibits an average of 70% loading factor from Shanghai to each EP. Transportation from the EPs to the DCs occurs by heavy-duty trucks and rail transportation, while from the DCs to the RSs by delivery truck transportation.

5.1 Deep-sea shipping freight rates

In order to estimate the freight rates per FEU from Shanghai to the EPs for Options A and C, we consider: (1) the freight rates of the current Option B, which have been estimated through the Freight Calculator (2018), and consitute the basis for estimating the freight rates in Options A and C; (2) the city of France "Cote d' Opale" as the start-point of the North Sea ECA; (3) the vessel's travel time of 0.4 days from Le Havre to Cote d' Opale, 0.6 days from Cote d' Opale to the port of Rotterdam and an additional 1 day from the port of Rotterdam to that of Hamburg; (4) the vessel's voyage times as in Table 5; (5) the vessel's fuel consumption of 130 tons per day at sea at the speed of 16 knots; and (6) the value of 361.4€ and 545.7€/ton of IFO 380 and ULSFO respectively (Ship and Bunker 2018). To this end and as we could not find cost data for the bunkers that meet the 0.5% m/m SOx limit requirements, we assume that the price per ton of fuel is approximately 10% less than the price of the ULSFO. Given the above, the derived deep-sea shipping freight rates for all options of Table 1 are summarized in Table 6.

5.2 Transportation costs per 40ft container

In order to estimate the heavy-duty truck, the barge and the rail transportation costs per 40ft container in the routes of the network under study, we employed the relevant mode transportation distances between the nodes of the network under study and the transportation cost parameters of the following Table 7, retrieved through personal communication by 3PLs active in EU region. For delivery trucks we consider transportation costs for each route as retrieved from 3PLs only.

The derived transportation costs from the Entry Ports to the DCs and from the DCs to the RSs are summarized in Tables 14, 15, 16, 17 of "Appendix 1".

Table 5 Sea-voyage times in days

LP/EP	Hamburg	Marseille	Trieste	Le Havre	Rotterdam	Piraeus
Shanghai	28	22	21	26	27	20

Table 6 Current Freight rate costs per FEU from Shanghai in all options

Options	Hamburg	Marseille	Trieste	Le Havre	Rotterdam	Piraeus
A	1582	1245	2026	2057	1567	1217
B	1591	1245	2026	2057	1576	1217
C	1669	1310	2088	2134	1656	1276

Table 7 Transportation cost parameters EP-DC

Cost Parameter/Mode of Transport	Rail	HD Truck	Barge
Fixed Cost of Transportation (€/40 ft container)	100	0	60
Variable Cost of Transportation (€/40 ft container/km)	0.5	2	0.4

Table 8 DC operating costs per year in Piraeus. *Source*: Mallidis et al. (2014)

Capacity in m3	Capacity in 40ft containers (FEUs)	Operating costs per year
100,000	1477	1,000,100
39,580	585	800,080
32,400	479	576,335
14,112	208	243,455
8400	124	255,500
2000	30	79,205
1000	15	54,750

5.3 DC operating costs

The DC operating costs per year are estimated considering data of the operating costs of various DC capacities in Greece, provided by Mallidis et al. (2014), as these are summarized in Table 8. These data have been then further adjusted to each DC's city wages considering each city's average wage ratio to that of Piraeus. Given the derived data we formulated the following DC operating costs in Table 9.

5.4 DC capacity level

In order to estimate the capacity level of each DC, we consider a cycle stock service level type I constraint, $\alpha = 95\%$, a coefficient of variation of daily demand cv=b=30% a review period of 14 days which is common for all the DCs, and the lead times from Shanghai to the EPs and to the DCs for each mode *m*, as these are summarized in Tables 18, 19 and 20 of "Appendix 2".

6 Numerical results

Three instances of the problem were solved, one for each option of Table 1. The developed model consists of 280 variables and 306 constraints. The results as depicted in Table 10 indicate that the optimal distribution structure of Option A involves the utilization of three

Table 9 Adjusted DC operating and depreciation costs per year of each DC

FEUs	Costs per FEU per year (in 000)									
	Venl.	Paris	Frank.	Berl.	Prag.	Wars.	Ath.	Mil.	Bud.	Buch.
1477	1533	1562	1504	1504	836	768	986	1380	754	614
585	1226	1249	1203	1203	669	614	789	1104	603	491
479	883	900	867	867	482	442	568	795	435	354
208	373	380	366	366	204	187	240	336	184	149
124	392	399	384	384	214	196	252	353	193	157
30	121	124	119	119	66	61	78	109	60	49
15	84	86	82	82	46	42	54	76	41	34
Per FEU	**2.8**	**2.9**	**2.8**	**2.8**	**1.5**	**1.4**	**1.8**	**2.5**	**1.4**	**1.1**

Bold value indicates average cost per FEU considering different DC capacities in each country

Table 10 Optimal SC network configuration and costs

Options	Entry ports		No. of DCs	Transp. Mod.		Cost (000 €/year)		
						Sea	Land	Total
A	Hamburg	(53%)	7	Truck	(0.0%)	16,416	6222	22,638
	Rotterdam	(41%)		Rail	(5.5%)			
	Piraeus	(6%)		Barge	(94.5%)			
B	Hamburg	(53%)	7	Truck	(0.0%)	16,529	6222	22,751
	Rotterdam	(41%)		Rail	(5.5%)			
	Piraeus	(6%)		Barge	(94.5%)			
C	Hamburg	(53%)	7	Truck	(0.0%)	17,351	6222	23,573
	Rotterdam	(41%)		Rail	(5.5%)			
	Piraeus	(6%)		Barge	(94.5%)			

out of the six entry ports, namely those of Hamburg, Rotterdam and Piraeus, seven out of the ten DCs in Venlo, Frankfurt, Berlin, Prague, Warsaw, Athens and Bucharest, and the inbound from the EPs to the DCs, transportation modes of rail and barge. The results also reveal that the implementation of Options B and C will not affect the shipper's supply chain structure, but will only lead to an increase of the total maritime supply chain costs. Specifically, under Option B the total maritime supply chain costs will increase by 0.5%, while under Option C by 4.1%. The main reason that justifies the results hinges upon the cost efficient inland barge transportation connections of Rotterdam and Hamburg to the EU hinterland, which seems to compensate the higher freight rates at these ports due to the employment of more expensive SOx limit complaint fuel.

To further evaluate the impact of different SOx limit compliant fuel prices on the shipper's supply chain we conducted sensitivity analysis on different ratios of the SOx compliant fuel to the IFO fuel. We denote the 0.5% and 0.1% m/m SOx limit compliant fuel prices per ton by $F^{0.5}$and $F^{0.1}$ respectively, and the IFO fuel price per ton by F^{IFO}. We then determine the following two ratios: $p^{0.5} = \frac{F^{0.5}}{F^{IFO}}$ and $p^{0.1} = \frac{F^{0.1}}{F^{IFO}}$. C onsidering the current value of $p^{0.5} = 1.36$, and $p^{0.1} = 1.51$, and by increasing the ratios by a 0.05 step, we derive the results of the following Tables 11, 12 and 13. The derived results indicate that the shipper's supply chain structure will change for the values of $p^{0.1} = 1.66$ and $p^{0.5} = 1.51$. In particular, in Option A the container flows passing through Hamburg EP will increase, as the higher cost impact of the IMO SOx limit regulations on the freight rates of Hamburg EP are not imposed and thus, their freight rates are reduced. This will in turn lead to a higher utilization of rail transport as more containers are now transported from Hamburg's EP to Warsaw's DC through rail. In Option C, the container flows are rerouted from Rotterdam's EP to Marseille's EP, which in turn reduces the sea voyage distances traveled and thus, the magnitude of the impact of the more expensive low SOx content fuel on the network's shipping costs. Moreover, as Marseille lacks barge transportation connections among the operating DCs, but it has cost effective rail transportation connections, the network's barge utilization will be reduced, while the utilization of rail transportation will be increased.

Table 11 Optimal SC network configuration: $p^{0.5} = 1.41$ and $p^{0.1} = 1.56$

Options	Entry ports	No. of DCs	Transp. Mod.	Cost (000 €)		
				Sea	Land	Total
A	n/o change	n/o change	n/o change	16,362	6222	22,584
B	n/o change	n/o change	n/o change	16,529	6222	22,751
C	n/o change	n/o change	n/o change	17,545	6222	23,767

Table 12 Optimal SC network configuration: $p^{0.5} = 1.46$ and $p^{0.1} = 1.61$

Options	Entry ports	No. of DCs	Transp. Mod.	Cost (000 €)		
				Sea	Land	Total
A	n/o change	n/o change	n/o change	16,324	6222	22,546
B	n/o change	n/o change	n/o change	16,529	6222	22,751
C	n/o change	n/o change	n/o change	17,802	6222	24,024

Table 13 Optimal SC network configuration: $p^{0.5} = 1.51$ and $p^{0.1} = 1.66$

Options	Entry ports		No. of DCs	Transp. Mod.		Cost (000 €)		
						Sea	Land	Total
A	Hamburg Rotterdam Piraeus	(59%) (35%) (6%)	7	Truck Rail Barge	(0.0%) (11.1%) (88.9%)	16,278	6389	22,668
B	Hamburg Rotterdam Piraeus	(53%) (41%) (6%)	7	Truck Rail Barge	(0.0%) (5.5%) (94.5%)	16,529	6222	22,751
C	Hamburg Rotterdam Marseille Piraeus	(53%) (21%) (20%) (6%)	7	Truck Rail Barge	(0.0%) (43.4%) (73.6%)	17,311	7004	24,315

7 Conclusions and future research

This study is a first-time effort that aims to quantify the impact of the current and future IMO sulphur limit regulations on the overall maritime supply chain, through the development of a MILP model. The model's applicability was implemented in the case of a refrigerator exporter in the EU market using realistic cost and time parameters. The results revealed that the implementation of the current and future IMO regulatory frameworks will not affect the shipper's distribution structure, but it will only lead to an increase of the total maritime supply chain costs due to the higher freight rates that the shipper will pay. This is because of the efficiency of the barge transportation connections from Hamburg and Rotterdam which make these particular ports preferable by the shippers even though they have to suffer higher freight rates. However, the results are case dependent as they may change for different ECAs, product types, and parameter accuracies. To further evaluate the sensitivity of the optimal solutions, sensitivity analysis was conducted on different values of the $p^{0.5}$ and $p^{0.1}$ ratios. The results demonstrate that changes in the shipper's distribution structure can occur after relatively low SOx limit compliant fuel price increases, and it involves changes in the container flows through EPs along with changes in the transportation modes employed from the EPs to the DCs.

Regarding the possible implications of these policies, these may occur depending on the whether the carrier will pass the resulted voyage cost increases on the freight rates to the shipper's or not, as this may lead shippers to select alternative EPs as start-points of their supply chain. Finally, future research perspectives involve the evaluation of the imposed IMO regulatory framework on the shipper's inventory planning decisions as it may lead to the selection of different EPs, and thus to higher lead times to the DCs.

Appendix 1: Inbound and outbound transportation costs per mode of transport

See Tables 14, 15, 16 and 17.

Table 14 Truck Transportation Costs from the EPs to the DCs

EPs	DCs									
	Venl	Par.	Fra.	Berl.	Pra.	War.	Ath.	Mil.	Bud.	Buch.
Hamb.	876	1845	1005	592	1276	1770	5342	2513	2429	4068
Mars.	2285	1651	2227	3269	2942	4228	5297	1097	3124	4396
Trieste	2543	2964	2471	2359	1670	2496	3560	885	1228	2867
Havre	1171	454	1610	2399	2651	3524	6534	2515	3714	5408
Rot.	324	1001	983	1494	1950	2605	6098	2402	3014	4661
Pira.	5710	6097	5133	4856	4120	4855	50	3632	3032	2333

Table 15 Rail Transportation Costs from the EPs to the DCs

EPs	DCs									
	Venl.	Par.	Frank.	Berl.	Prag.	Wars.	Ath.	Mil.	Bud.	Buch.
Hamb.	310	557	354	247	427	527	1439	694	704	1116
Mars.	672	478	602	864	875	1119	1461	381	866	1279
Trieste	703	697	564	682	497	713	1010	306	416	828
Havre	402	237	494	681	819	961	1703	617	994	1406
Rot.	178	343	314	440	584	721	1548	635	813	1225
Pira.	1473	1593	1339	1122	1134	1243	106	1209	845	845

Table 16 Barge Transportation Costs from the EPs to the DCs

EPs	DCs									
	Venl.	Par.	Frank.	Berl.	Prag.	Wars.	Ath.	Mil.	Bud.	Buch.
Hamb.	302	n/a	364	190	319	n/a	1542	n/a	816	1220
Mars.	n/a	n/a	n/a	n/a	n/a	n/a	851	500	n/a	n/a
Trieste	n/a	n/a	n/a	n/a	n/a	n/a	652	239	n/a	n/a
Havre	n/a	170	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Rot.	118	n/a	248	486	461	n/a	n/a	n/a	691	1135
Pira.	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a represents a route where no barge connections exist

Table 17 Delivery Truck Transportation Costs from the DCs to the RSs

DCs	RSs									
	Eindh	Sof.	Prag.	Cop.	Mun.	Berl.	Ham.	Frank	Riga	Ath
Venlo	92	3190	1186	1159	1047	930	662	478	2729	4292
Paris	672	3479	1633	1895	1338	1689	1395	943	3451	4588
Frank.	533	2753	803	1282	619	868	771	38	2651	3714
Berlin	1039	2554	539	683	949	38	463	868	1838	3663
Prag.	1268	2017	38	1218	603	539	997	783	2020	3126
Wars.	1852	2580	1045	1557	1667	889	1336	1638	991	3678
Ath.	4377	1218	3126	4336	3239	3667	4116	3713	4655	50
Milan	1621	2201	1477	2349	878	1735	1852	1163	3460	2723
Bud.	2086	1195	836	2053	1116	1380	1800	1370	2133	2297
Buch.	3353	552	2100	3317	2380	2648	3088	2833	3009	1776

Appendix 2: Lead times from Shanghai to the EPs and on to the DCs per mode

See Tables 18, 19 and 20.

Table 18 Lead time (days) from Shanghai to the EPs onto the DCs (Ship+Truck)

EPs	DCs									
	Venl.	Par.	Frank.	Berl.	Prag.	Wars.	Ath.	Mil.	Bud.	Buch.
Hamb.	29	29	29	29	29	29	30	29	29	30
Mars.	23	23	23	24	23	24	24	23	24	24
Trieste	22	22	22	22	22	22	23	22	22	22
Havre	27	27	27	27	27	28	29	27	28	28
Rot.	28	28	28	28	28	28	30	28	28	29
Pira.	22	23	22	22	22	22	21	22	22	21

Table 19 Lead time (days) from Shanghai to the EPs onto the DCs (Ship+Rail)

EPs	DCs									
	Venl.	Par.	Frank.	Berl.	Prag.	Wars.	Ath.	Mil.	Bud.	Buch.
Hamb.	29	30	30	29	30	30	34	31	31	33
Mars.	24	23	24	25	25	27	28	23	25	27
Trieste	24	24	23	24	23	24	25	22	23	24
Havre	28	27	28	29	29	30	33	29	30	32
Rot.	28	28	28	29	29	30	33	30	30	32
Pira.	26	27	26	25	25	25	21	25	24	24

Table 20 Lead time (days) from Shanghai to the EPs onto the DCs (Ship+Barge)

EPs	DCs									
	Venl.	Par.	Frank.	Berl.	Prag.	Wars.	Ath.	Mil.	Bud.	Buch.
Hamb.	31	n/a	32	30	32	n/a	46	n/a	37	42
Mars.	n/a	n/a	n/a	n/a	n/a	n/a	27	25	n/a	n/a
Trieste	n/a	n/a	n/a	n/a	n/a	n/a	24	24	n/a	n/a
Havre	n/a	28	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Rot.	28	n/a	30	32	32	n/a	n/a	n/a	35	40
Pira.	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

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