Towards low carbon global supply chains : a multi-trade analysis of CO_2 emission reductions in container shipping

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Abstract

This paper focuses on understanding the carbon footprint associated with international maritime container supply chains. Although extensive studies exist on the impact of international shipping at a global scale, few tools and empirical papers are available to assess the progress made so far in the shift towards carbon clean maritime supply chain. Hence, there is the need for establishing a more transparent methodology to assess the amount and intensity of CO_2 emissions at a trade level, but also to better understand how results differ from one trade lane to another. For addressing this gap, our study analyzes the impact of the key contributing factors on the longer-term variation of CO_2 emissions in global container shipping. The following research objectives are pursued. First, we identify the key factors affecting CO_2 emissions by container ships based on extant literature and business insights. Second, we measure the evolution of the total CO_2 emissions by the container fleet in the past decade by offering multi-trade comparisons of the situations in 2007 and 2016. Third, we analyse to what extent the identified factors contributed to the observed changes in average CO_2 emissions between 2007 and 2016, again per trade lane. Fourth, we discuss how these findings could be used by shippers and logistics service providers when designing cargo routing solutions in a supply chain setting based on their carbon efficiency.

Keywords: container shipping, maritime supply chain, CO2 emissions, measurement, determinants, multi-trade analysis

1. Introduction

Firms operating on international markets are taking many initiatives in order to reduce and mitigate carbon emissions. However, as stated by Tiwary et al. (2015), these initiatives have largely focused on investment in new technology, in developing energy-efficient equipment and facilities while the reduction that could be achieved from a supply chain and logistics perspective has been subject to less attention. In this context, the selection of the appropriate supplier to reduce carbon emission is crucial and analytical tools and data are required.

Indeed, integrating environmental issues into production, supply chains, and logistics is a complex process and it has been addressed in a limited number of studies (Elhedhli and Merrick, 2012; Shaw et al. 2012). In an extensive review of 58 studies on cleaner practices in organizational processes (26 from International Journal of Production Economics and 32 from Journal of Cleaner Production), Subramanian et al. (2015) also conclude to a limited number of studies on green supply-chain management (Sarkis et al., 2011; Seuring and Müller, 2008; Caniato et al., 2012). For research related to purchasing, procurement and supplier-selection models, 75% of work is related to reverse logistics network design while forward logistics has been mostly examined through the use of web-based tools to assess the specific sustainability aspects of wine distribution, facility location, CO_2 reduction, and utilization (Cholette and Venkat, 2009; Harris et al., 2011; De Rosa et al., 2013). This led Subramanian et al. (2015) to conclude on the need for studies on different modes of transportation in the future, and in particular for further understand how a cleaner supplier-selection card can be developed.

This need is reinforced by recent literature that shows that transportation and logistics practices in supply chains are often the greatest source of environmental emissions and degradation for companies (Graham et al. 2018) and that there is an increasing pressure on companies to measure and report their carbon footprint (Pazirandeh and Jafari, 2013; Tang et al., 2015). In this context, studies should move beyond a manufacturing focus to consider environmental challenges emerging from supply chain process, such as logistics (Mejías et al., 2016) that account for up to 75% of the carbon emissions generated throughout the supply chain (Dey et al., 2011). In particular, special attention should be given to the management of global supply chains and long-haul transportation solutions, as the implied choices have a tremendous environmental impact at a local and an international scale.

This paper focuses on understanding the carbon footprint associated with international maritime container supply chains. If extensive studies exist on the impact of international shipping at a global scale, few tools and empirical papers are available to help firms in order to assess the contribution of the maritime component in carbon clean global supply chains. This could be of interest for companies such as Walmart, with more than 720 000 TEU imported from Asia in 2012 (+147 since 2002), Target, with 496 000 TEU (+187% since 2002), Home Depot (315 000 TEU and +73% since 2002 (Lister, 2015) or global freight forwarders that heavily rely on maritime supply chains for their international operation and distribution. These players can use better information on the global carbon footprint of container shipping activities to support the shift towards carbon low global supply chains.

First, information reported by international organizations is far too aggregated. At most, one can know that in 2012 (using the latest IMO update of 2014) a 14 000 TEU containership is emitting less CO2 per TEU than, for instance, a 10 000 TEU vessel, and that slow steaming practices extensively used by the industry since 2008 have led to a reduction of approximatively 15%-20% of emissions (Cariou, 2011; IMO 2014). Second, studies for which more detailed information is available, such as on the amount of CO_2 emissions in grams per TEU-km per trade or trade CO_2-intensity from the BSR Clean Cargo Group (2016), are reporting an average-industry indicator, without a clear explanation on the methodology used. Hence, there is the need for establishing a more transparent methodology to assess the quantity and intensity of CO_2 emissions at a container trade level, but also to better understand how results differ from one trade to another.

This paper analyzes the impact of the key contributing factors on the longer term variation of CO_2 emissions in global container shipping. We put forward the following research objectives. First, we identify the key factors affecting CO_2 emissions by container ships based on extant literature and business insights. Second, we measure the evolution of the total CO_2 emissions by the container fleet in the past decade by offering multi-trade comparisons of the situations in 2007 and 2016. Third, we analyse to what extent the identified factors contributed to the observed changes in CO_2 emissions between 2007 and 2016, again per trade lane. Fourth, we discuss how these findings could be used by shippers and logistics service providers when designing cargo routing solutions in a supply chain setting based on their carbon efficiency.

The paper is structured as follows. In the next section, we present a list of key contributing factors to the CO2 emissions levels of the global container shipping fleet based on a literature review and insights from a business perspective. In Section 3, we develop a model to estimate the total CO_2 emissions in container shipping per trade lane. Section 4 presents the input data required in order to apply our model and Section 5 provides estimates for 187 container services deployed in 2007 and 170 services in 2016. Section 6 discusses how our results could be used by shippers and logistics service providers in the design of carbon low global supply chains and Section 7 concludes.

2. Identification of factors contributing to changes in maritime carbon emissions

To meet the first objective of this research paper, we identify the key factors affecting changes in CO_2 emissions by container ships in the past decade based on extant literature and business insights. Container shipping is recognized as a resource-intensive industry that needs to be accountable in terms of environmental sustainability both during navigation at sea and in ports (Bouman et al., 2017). The latest release of the greenhouse gas study (GHG) of the International Maritime Organization (IMO, 2014) recognizes that shipping reduced CO_2 emissions by over 15% compared to 2012. Nonetheless, a huge effort for further emission abatement in shipping is needed at international level in order to actively contribute to respect the global emission targets in the long-term (Anderson and Bows, 2012).

Over the past decade, the shipping industry experienced profound changes both at operational and strategic levels that reshaped the competitive paradigms among shipowners and had an impact on the CO_2 emissions of the ship fleet. It is worthwhile investigating to what extent such far-reaching changes in the container shipping industry have impacted on the reduction of total CO_2 emissions. A broad stream of studies has documented the progressive reduction of shipping emissions worldwide by adopting two main approaches (Bouman et al., 2017). Some papers attempted to estimate the total reduction in CO_2 emissions in the shipping industry, while also assessing associated developments (Alvik et al., 2010; Lindstad et al., 2015). The estimations provided in terms of measurement unveil ranges of variations which are very broad and unreliable (see Bouman et al., 2017). A second group of studies dealt with the various measures which are implemented for abating CO_2 emissions in the industry. These contributions undertook narrower and more focused analyses also trying to disentangle the (individual) impact of the sample of measures on global emissions (Corbett et al., 2009; Cariou, 2011; Perera and Mo, 2016). However, extant literature provides little insights on the respective contribution of the factors explaining the changes in worldwide CO_2 emissions from international container shipping. Furthermore, not all drivers of change of ships' CO_2 emissions are being discussed, and some possible contributing factors such as the increase in port productivity remain rather neglected so far.

Academic literature recognizes that numerous factors affect the amount of CO_2 emissions. Commonly, emission reduction measures are split in two main categories, i.e. technical and operational (Psaraftis, 2016). The former group is related to the introduction of more efficient ship design, upgraded propulsion and power systems, innovative fuels, etc. (Faber et al., 2011;

Gilbert et al., 2014; Lindstad et al., 2015). The latter group includes measures for emission reduction during shipping operations, such as commercial speed optimization, vessel trim optimization, optimal route planning, on board energy management, capacity management, etc. (IMO, 2009; Lin, 2012; Tillig et al., 2015). All these measures are typically undertaken with the main objective of reducing emissions, although they yield benefits in the pursuit of economic goals as well, such as the realization of savings in total ship operating costs.

Ship operators' commercial or financial decisions might potentially increase or decrease emissions without being explicitly linked to any green strategy adopted by firms. For example, decisions on the vessel size to be deployed and on the commercial vessel speed are two strategic choices that might heavily affect ship/fleet emissions but primarily relate to other decisional areas (e.g. financial equilibrium, commercial strength, etc.).

Based on extant literature and operational practices in container shipping, we identify six factors driving changes in CO2 emissions in container shipping (Fuel Type & Efficiency, Vessel Size; Vessel Number; Number of Port & distance travelled; Commercial Speed and Time in Port), as documented in Figure 1, which also shows the main players driving changes in each of them.

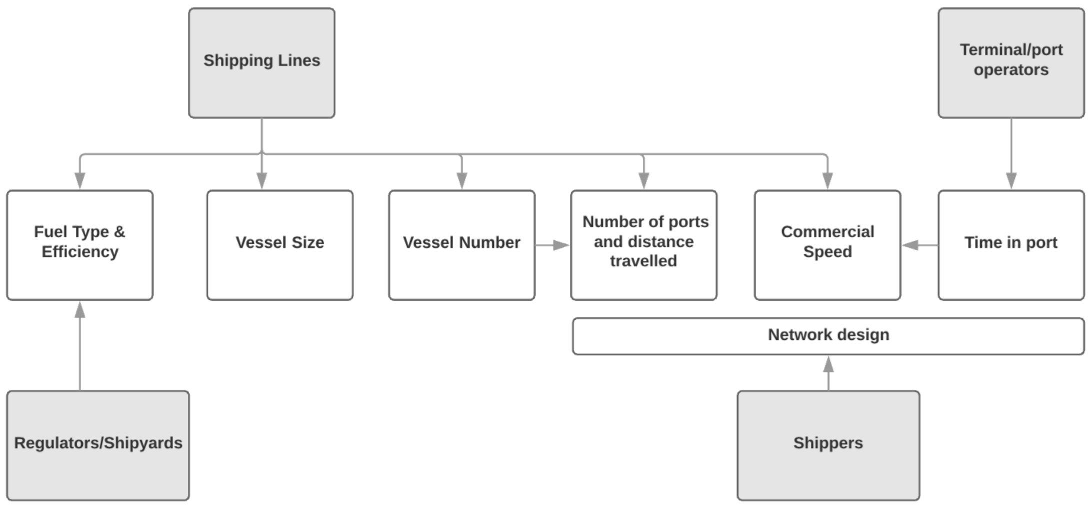


Figure 1. The actors and the decision factors influencing the variation of total CO_2 emissions in container shipping

A first factor (Fuel Type & Efficiency) deals with the introduction of technological innovations in propulsion, machinery systems and hull design. The utilization of cleaner fuel types to meet the regulatory stipulations of IMO (e.g. Marpol Annex VI) coupled with more efficient engines have the potential to reduce emissions considerably (Wärtsila, 2009; Wang and Lutsey, 2013;

Tillig et al., 2015). In addition, modern hull shapes of mega-ships are optimized for reduced drag, thus lowering fuel consumption and CO_2 emissions (Stott and Wright, 2011; CCNR, 2012; Gilbert et al., 2014). The above technological improvements have been stimulated by the need to comply with new compulsory regulations issued at international level. Hence, regulators, shipyards and shipowners are the main protagonists of such green innovations.

Another relevant factor that enabled liner shipping services to reduce emissions per shipped container relates to scale increases in container ship size (Vessel Size). The ordering of mega-vessels by shipowners has as primary goal the pursuit of economies of scale for corroborating cost leadership strategies (Imai et al., 2006; Tran and Haasis, 2015). Nonetheless, the massification of demand over bigger vessels also enabled shipping lines to reduce the environmental impact in relative terms, i.e. lowering emission intensity (grams of CO_2 per TEU-km) (Lindstad et al., 2012; Gucwa and Schäfer, 2013). Shipyards exploited technological innovation for realizing robust mega-ships with hull shapes and engine optimization as reported above.

A third factor is the rise of the number of vessels deployed globally (Vessel Number). First, the extension of transit times because of the lower commercial speed required the deployment of a higher number of vessels for each service loop (Ronen, 2011). Inevitably, this leads to higher emissions, all other things being equal (Corbett et al., 2009; Ferrari et al., 2015). Second, from a shipping network perspective, increased global (maritime) trade volumes result in a higher demand for shipping services and thus urge shipping lines to deploy a higher fleet capacity throughout the network. If these trade flows involve nations located far away from each other, then more ships per liner service will be needed in view of offering a weekly departure in each port of call along the route.

A fourth contributing factor (Number of ports and distance travelled) relates to the sailing distance covered by an individual ship or an entire fleet (in nautical miles or km). At the level of an individual liner service, reductions in the sailing distance on a specific trade route can be achieved by an optimization of weather routing and scheduling, leading to the use of more effective sailing routes and navigating through areas with easier weather conditions (Miola et al., 2011). In addition, ocean carriers can adopt more restrictive policies for port selection (i.e. a reduction in the number of ports of call in the liner service) and minimize deviations from ideal routes thereby reducing ships' diversion distances. For this factor, as well as for the last two elements, shippers play a crucial role in setting the optimal network design as changes in their supply chain obviously impact the choice made by shipping lines and the sailing distances covered by the entire fleet deployed also depend on the dynamics in global trade volumes. Sailing distances per roundtrip and associated fleet emissions decrease when trade increasingly takes place between nations located closer to one another.

Closely associated with vessel size, we find the optimization and the decrease of the average commercial speed of vessels (Corbett et al., 2009; Lindstad et al., 2011). The introduction of slow steaming practices dates back to 2008 when shipping lines needed to reduce bunker consumption to drastically cut operating costs (Notteboom and Vernimmen, 2009; Cariou, 2011). Slow steaming practices were first initiated when bunker costs rose significantly in only a few years' time, from a level of USD 200-250 per tonne to above USD 700 per tonne in the Summer of 2008 (figures for IFO380 grade heavy fuel). After the start of the financial-economic crisis in late 2008 early 2009, this practice also gave ocean carriers the possibility to reduce the overall supplied transport capacity (TEU-km), thus absorbing some of the vessel overcapacity, and to reduce ship operating costs in times of extremely low freight rates. The stabilization of vessels' commercial speed at lower levels yielded cost savings and operational advantages for ocean carriers. However, it also had ripple effects throughout the supply chains, exemplified by the longer cargo transit times for shippers (customers) combined with only modest schedule reliability improvements. Finally, speed optimization across various trade lanes enabled to reduce CO_2 emissions, thanks to the adoption of speed levels well below the hydrodynamic boundary thus minimizing resistance and fuel consumption (Psaraftis and Kontovas, 2013; Bouman et al., 2017).

Finally, changes in port productivity, that is under port/terminal operators, are a last factor inducing changes in CO2 emissions by ships (Time in port). For a given ship capacity in TEU, an increased port/terminal productivity positively affects the total time spent by vessels in port, thereby contributing to a shorter port turnaround time and a shorter total round voyage time of the ship. Productivity enhancements can come in different forms, including a more efficient port approach and ship manoeuvring, bigger and faster ship-to-shore cranes, a higher crane density per ship, larger terminals requiring lower dwell times and so on (Felício et al., 2015; Ha et al., 2017). These changes enable vessels to dedicate comparatively more time to navigation while making a round voyage in the context of a regular liner service. Many players are involved in the management of the logistics chain in port operations and favour the rise of the operating performance of ports and terminals. Shipping lines are increasingly putting pressure on terminal operators to increase terminal productivity as they want to avoid that the scale increases in vessel size result in longer port stays. Hence, terminal operators have invested huge amounts of money in state-of-the-art quayside and yard equipment and new ICT systems as well as for improving organizational routines (Olivier, 2005). Shipping lines, as terminal customers, have been able to enhance collaborative forms of data exchange and operational coordination with terminal operators, bringing a decisive contribution to more efficient mechanisms of service co-production.

All these measures decrease fuel consumption and associated emissions (Psaraftis, 2016) and impact the level of emissions at a trade or liner service level.

3. Model specification

In the previous section we have identified the main factors that potentially contribute to changes in the CO_2 emissions of container shipping. In view of meeting the two remaining research objectives (i.e. measuring the evolution of the total CO_2 emissions by the container fleet and to analyse to what extent the identified factors contributed to the observed changes in CO_2 emissions), we develop a model to estimate the total CO_2 emissions in container shipping per trade lane. These estimates are obtained by developing three modules as presented in Figure 2.

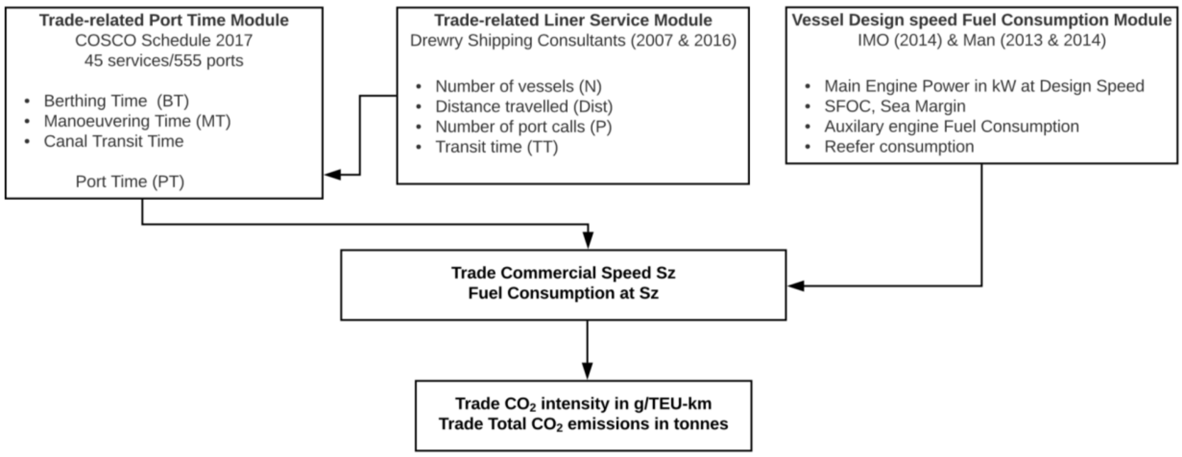


Figure 2. Main determinants of trade-related CO_2 intensity and total CO_2 emissions

The total amount of CO_2 emission per ship in a year (Psaraftis et Kontovas 2008) is a function of the CO_2 emission factor (E_f in g per tonne of fuel), of the proportion of time at sea (s) and in port (p=1-s), of the average fuel consumption at sea (F in tonne per day), in port (G in tonne per day) and of the number of operating days in a year (D). On the main liner shipping routes, a weekly frequency is usually required (Ronen 2011; Ducruet and Notteboom, 2012), each service comprises several vessels (N=Total Transit Time in days/7) and services are provided all year long (D=365). Therefore, the total CO_2 emission for a service i in a year (CO_2), for an emission factor E_f, equals to:

$$\text{Annual } CO_2 \text{ (in tonnes)} = E_f.(s.F + p.G).D.N \quad (1)$$

Total emissions can also be expressed as a function of the CO_2 intensity in grams of CO_2 per TEU kilometer with:

$$\text{Annual } CO_2 \text{ (in tonnes)} = CO_2 \text{ Intensity.(Distance in a year).(Capacity Deployed)} \quad (2)$$

With CO_2 Intensity in grams of CO_2 per TEU-km = $E_f.(F+(p/s).G)/(TEU.S_z.24)$

Distance in nm in a year = (Distance).(365/TT)

Capacity Deployed = (N.TEU)

The proportion of time at sea (s) depends on the total transit time (TT), on the number of ports within a service (P) and on the average time spent in port (PT) that includes waiting, manoeuvring or at berth (BT). The commercial speed (S_z) is then S_z=(TT-PT)/TT.

Finally, knowing the time spent at sea and in port (s and 1-s), the average amount of emissions per vessel then depends on the determination of the average fuel consumption at sea (F) and in port (G). The fuel consumption in port (G), when cold ironing is not available, is mostly from the auxiliary engine consumption (G_A) during port operations and changes with vessel size and engine characteristics. To determine F, consumption from two different engines are usually considered (Psaraftis 2008; Corbett et al. 2009; Cariou, 2011; Wang and Meng, 2012). For the main engine (F_{ME}), the fuel consumption which is a function of the consumption at design speed (F_{ds}), of the elasticity of fuel consumption to speed with F, usually assumed to be a cubic function of S_z and of a sea-margin (s_m) to account for weather and sea conditions. At design speed, the fuel consumption per day depends on the engine kW and on the Specific Fuel Oil Consumption SFOC (in g/kW). For the auxiliary engine at sea (F_A), the fuel consumption is independent to speed and changes with vessel size, with the engine characteristics and with additional consumption related to the number of reefer containers onboard the vessel. For a commercial speed equal to S_z, the total amount of Fuel consumed in tonnes per day at sea for the main and auxiliary engines is:

$$F=F_{ME}+F_A=S_m.F_{ds}.(S_z/S_{ds})^3+F_A=(24.SFOC.kW).(S_z/S_{ds})^3+F_A \quad (3)$$

4. Input data

4.1. Selection of years of observation

In the empirical part of this paper, we use data for 2007 and 2016, thus covering a period of almost a decade. This period of observation is sufficiently long to observe longer term trends and changes in CO_2 emissions in the maritime segment of global supply chains. The choice for 2007 and 2016 as years of observation was also inspired by the large differences in market and operational conditions in container shipping between both years, making a comparison more valuable.

First, pre-crisis year 2007 was characterised by bullish market conditions in container shipping which started at the beginning of the new millennium. This booming period in container shipping brought high vessel and container terminal utilization rates, healthy freight rates, and a strong market sentiment. Confidence levels in the market plummeted in late 2008 when the financial-economic crisis hit most parts of the world (Notteboom et al., 2010). The resulting situation of vessel and terminal overcapacity, low freight rates, negative or very low operating margins of carriers and harsh market conditions affected the container shipping market for many years to come, and forced shipping lines to focus on cost control. Even the year 2016 was still characterised by very low freight rates (e.g. record lows on the Europe-Far East trade in early 2016), negative operating margins for most operators (Alphaliner, 2017) and ample availability of container terminal capacity in world ports.

Second, there are noticeable differences in the market structure and coverage between the two years of observation. The container shipping market was already somewhat concentrated in 2007 following M&A activity (such as the take-over of P&O Nedlloyd by Maersk line in 2006). Market consolidation reached new heights in 2016 following the bankruptcy of Hanjin and large scale mergers and take-overs between 2014 and 2016 affecting companies such as China Shipping, Cosco, UASC, Hamburg Sued, APL/NOL, OOCL and others. The remaining global carriers further enlarged the global reach of their liner service networks. Moreover, the carrier alliance landscape changed significantly during the period of observation (Notteboom et al., 2017). In 2007, three alliances were active on the main east-west trade lanes i.e. New World Alliance, Grand Alliance and CKYH. By 2016, consecutive rounds of alliances reshuffles resulted in 2M (Maersk Line and MSC), THE Alliance (Hapag Lloyd, Yang Ming, MOL, NYK and K-Line) and Ocean Alliance (COSCO, OOCL, Evergreen and CMA CGM).

Third, the operational characteristics of fleet and vessel deployment changed between 2007 and 2016 as will be demonstrated in the next section. Major changes can be found at the level of vessel speed (i.e. the introduction of slow steaming from 2008 onwards), sailing distances, vessel size, port call patterns, port time, etc.

4.2 Liner service network

The dataset on liner service characteristics was developed using raw data from Drewry Container Forecaster for 2007 and 2016. We selected information for weekly services with containerships of more than 1 000 TEU (two-stroke engines) and for services with more than 5 vessels deployed. For each service, information was collected on the service name, the transit time, the number and the average size of vessels deployed, the trade where vessels are deployed and on the list of all ports where vessels are calling. We merged the initial dataset with information on port-to-port distance (https://sea-distances.org/) to estimate the total distance travelled for each service (distance in nautical miles).

For services calling ports on different trades (for instance a pendulum and round-the-world service), we consider that the number of vessels affected to a trade is proportional to the number of calls in the respective regions. For instance, in the event of a pendulum service of 15 vessels which includes 5 calls in Asia, 5 calls in Europe and 5 calls in North America, we assume that the equivalent of 10 vessels are operating on the Asia-Europe trade and 5 vessels for the Europe-North America trade. On a yearly basis, as the transit time is 105 days (7x15 vessels), it means that for this service, the total number of vessels operating on the Europe-Asia trade is 34.8 (10x(365/104)) and on the Europe-North America trade is 17.4.

Table 1 presents some descriptive statistics aggregated for 8 trade routes. There were 187 liner services deployed in 2007 and 170 services in 2016, corresponding to 1 228 and 1 373 vessels respectively. Descriptive statistics show a general increase in vessel size, from 3 463 TEU on average in 2007 to 5 862 TEU in 2016 (+69%), with some differences across the various trade routes. The trade lane subject to the largest increase in average vessel size is Asia-South America (+153%) followed by Asia-Europe (+94%).

As expected, in 2016, the largest vessels are deployed on Asia/Europe (vessel unit capacity of 11 210 TEU on average). Furthermore, the generalization of slow steaming since 2008 implied an increase in transit time on almost all trades, with 25% increase on average. The largest increase is on Asia-Europe (34%) and Europe-South America (32%). There is a slight increase in the average number of ports of call per service from 12.7 to 14.4 calls. When accounting for changes in the number of vessels and in transit time, the total number of calls in a year (-1.6%) and the total distance travel in a year (-6.0%) remain fairly stable, to the notable exception of Europe-Africa (-20% in calls and -26% in distance travelled).

Table 1. Characteristics of container liner services in 2007 and 2016

	2007						
Trade	**Service #**	**Vessels #**	**Size Av. TEU**	**Transit time Av. days**	**Call Av. #**	**Call Year #**	**Distance 000 nm Year**
Asia-Africa	13	90	2 647	60.3	12.2	6 671	11 100
Asia-Europe	45	346	5 783	59.0	14.0	30 061	47 300
Asia-North America	60	360	4 838	48.8	10.8	29 178	50 600
Asia-South America	12	111	2 636	70.6	16.3	9 343	15 100
Europe-Africa	8	42	2 720	39.4	9.8	3 753	3 967
Europe-North Am	26	142	3 531	49.2	12.5	13 177	17 900
Europe-South Am.	13	78	3 009	42.5	13.0	8 701	9 015
North Am.-South Am.	10	59	2 542	41.3	12.9	6 726	6 746
Mean/Total	**187**	**1 228**	**3 463**	**51.4**	**12.7**	**107 611**	**161 727**
	2016						
Trade	**Service #**	**Vessels #**	**Size Av. TEU**	**Transit time Av. days**	**Call Av. #**	**Call Year #**	**Distance 000 nm Year**
Asia-Africa	12	105	4 239	78.2	12.7	6 186	10 500
Asia-Europe	43	423	11 210	79.1	16.2	31 642	47 000
Asia-North America	52	399	6 397	64.1	11.7	26 575	46 900
Asia-South America	12	123	6 674	83.4	17.0	9 149	14 900

Europe-Africa	5	32	4 033	50.4	13.0	3 012	2 930
Europe-North Am.	25	145	4 778	53.2	14.2	14 135	15 200
Europe-South Am.	12	91	5 127	56.0	15.2	9 015	8 945
North Am.-South Am.	9	56	4 438	49.8	15.1	6 201	5 600
Mean/Total	**170**	**1 373**	**5 862**	**64.3**	**14.4**	**105 914**	**151 974**

4.3 Time in port

In order to estimate the fraction of time of a service spent in ports (p), we first rely on information provided by COSCO Shipping Line (2017) on the number of hours scheduled at berth (BT) for 555 port calls corresponding to 45 services. For each service, we added information (http://www.containership-info.com/) on the average size in TEU of vessels per service. Ports of call within services were then grouped into 10 regions (R), and berthing time was estimated as follows

$$\ln(BT)=a+b.\ln(TEU)+c.R \quad (4)$$

Where BT is the time at berth in hour, TEU is the average vessel size and R is a set of 9 regional dummies, with Asia/North Asia being used as reference category. Table 2 reports estimates for equation (4). Results show that a 1% increase in vessel size leads to a 0.177% increase in time at berth. This implies that scale increases in vessel size lead to a less then proportional increase in the time at berth. The extra port time normally brought by bigger call sizes of the larger vessels are thus partly compensated by a higher terminal productivity at berth (i.e. a higher crane density per vessel and or a higher number of moves per crane hour).When accounting for the regional location of operations, and compared to the reference category, berthing time is lower (-0.114) when a call takes place in Southern Asia (for instance Singapore, Hong Kong, Kaohsiung). This might be explained by the high sea-sea transshipment incidence and large call sizes in the region which simplify and speed up terminal operations (Rodrigue and Notteboom, 2010). Assuming that the same vessel calls in a Asian/North Asian port and in a South Asian port, the time spent at berth is then 10.8% lower (or exp(-0.114)-1) in South Asia. For all other regions, the time spent at berth is higher compared to Asia/North Asia. For a similar vessel, the highest time at berth is found in Africa (+195%) and in US West Coast (+104%), two markets dominated by gateway cargo and thus a low transshipment incidence.

Table 2. Estimates on Time at berth

	Coef	t-stat
Constant	1.373***	(4.97)
TEU size (in ln)	0.177***	(5.86)
South Asia	-0.114**	(-2.42)
South America	0.120**	(2.23)

North Europe	0.280***	(3.77)
South Europe	0.057	(1.01)
US West Coast	0.714***	(6.69)
US East Coast	0.340***	(2.84)
Middle East	0.064	(0.78)
Oceania	0.223***	(3.14)
Africa	1.081***	(7.24)
Asia/North Asia	Ref. category	
Observations	555	
R-squared	0.251	

*** p<0.01, ** p<0.05, * p<0.1
source: Authors from 2017 COSCO schedule data (http://lines.coscoshipping.com/home/)

Table 3 provides estimates on the time at berth per region, when considering the average vessel size calling per region in 2007 and in 2016. The average values from COSCO in 2017 and by Slack et al. (2018) for 2013 are also reported for the sake of comparison, although the characteristics of vessels calling might be different. For the same vessel, we have assumed that handling productivity at berth was 30% higher in 2016 than in 2007, in line with data reported for Australia (Waterline, 2015). However, the fact that vessels' size has increased means the time spent at berth reduced less than the handling productivity, with a general decrease of 17.1% in time at berth.

Table 3. Average Regional Time at Berth (BT) estimates in 2016 (in hours)*

	2007 Av. TEU	2007 BT	2016 Av. TEU	2016 BT	2007-2016 Evol BT	COSCO Schedule 2017	Total PT Slack et al.– (2018)
Asia/North Asia	4 711	22.7	7 726	18.9	-16.7%	21.8	23.5
South Asia	4 604	20.1	7 722	16.8	-16.4%	18.2	26.5
South America	3 616	24.5	4 696	19.7	-19.6%	24.6	23.5
South Europe	4 416	23.6	7 615	19.7	-16.5%	21.9	20.3
North Europe	4 695	29.8	8 202	25.0	-16.1%	31.3	29.5
US West Coast	4 849	46.7	6 716	37.9	-18.8%	44.1	46.2
US East Coast	3 684	30.6	5 033	24.9	-18.6%	29.8	21.1
Middle East	5 367	24.8	9 775	21.2	-14.5%	18.9	26.8
Oceania	2 800	25.9	4 118	21.5	-17.0%	23.2	-
Africa	2 584	60.2	4 427	50.5	-16.1%	53.1	64.6
Mean	**4 132**	**30.9**	**6 603**	**25.6**	**-17.1%**	**28.7**	**31.3**

* Estimations are retrieved from coefficient Table 2 and from equation 4 with $BT=Exp(a).(TEU)^b.Exp(c)$

The largest decrease in time at berth is in South America (19.6%), and the lowest decrease, due to an important change in vessel size, is in the Middle East (-14.5%). On average, our estimates on time at berth are lower than values reported by COSCO, the reason being that the average size of vessels included in the COSCO schedule (8 460 TEU) is larger than in our sample (6 582 TEU). Finally, the difference with Slack et al. (2018) can be related to the fact that those values are for 2013 and not for 2016, and that they are corresponding to the total time in port and therefore include the manoeuvring time in port.

To calculate the total time in port per call, we later assume that four additional hours are spent in each port for approach and manoeuvring, and that for the Asia-Europe trade, two days are spent for the transit through the Suez canal (both ways - note that a one-way Suez Canal transit takes about 11 to 16 hours of sailing time excluding the queuing time to form convoys). Table 4 presents estimates on the fraction of the time spent in port (p), the evolution in the number of vessels deployed (N) and on the commercial speed (S_z)[1] per trade. To determine the commercial speed (S_z) at trade level, we use information on the distance to travel for each service (Dist) and on the transit time at sea (Transit Time-Port Time) so that S_z=Dist/((TT-TP)).

Table 4 shows the general decrease in commercial speed from 20.9 kt in 2007 to 16.4 kt in 2016. Two main factors can explain these changes: either the decrease in time in ports due to the increase in port productivity (Table 3) or to changes in services characteristics (number of ports and distance, Table 1); and the increase in the number of vessels deployed (Table 1) as without any change in the network, lower speed can be achieved in adding vessels to a service. The lowest speeds are, on average, for vessels deployed on the Asia-Africa trade (14.4 kt in 2016) and the lowest decrease in commercial speed over the period is found for services deployed on the Asia-Europe trade route (-28%). On Asia-Europe trade, the decrease in speed is mostly explained by the reduction of time in port (-23%). On Europe-North America, the reduction of the time in port is more limited (-12%) due to the fact that there are more calls (+ 7% from Table 1). On Europe-Africa and North America-South America trade, the reduction of the time in port (-14%) is mostly due to to less vessels/services deployed (Table 1 with - 24% and -5% respectively).

Table 4. Fraction of time in port, number of vessels and commercial speed per trade

	Fraction of time in port (p)			Vessels #*	Speed in knots (S_z)		
Trade	**2007**	**2016**	**2016/2007**	**2016/2007**	**2007**	**2017**	**2016/2007**
Asia-Africa	26%	20%	-23%	17%	18.8	14.4	-23%
Asia-Europe	31%	24%	-23%	22%	22.9	16.6	-28%
Asia-North America	26%	18%	-31%	11%	21.8	16.3	-25%
Asia-South America	24%	19%	-21%	11%	20.8	17.3	-17%
Europe-Africa	44%	38%	-14%	-24%	19.6	16.7	-15%
Europe-North Am.	34%	30%	-12%	2%	21.5	17.5	-19%

[1] For each service, the time at sea is estimated by subtracting from the total transit time, the total time in ports (using the number of call and the time for each call for each subregion from Table 3) and in-transit through the Suez canal. For instance, for a transatlantic service with 5 calls in North Europe and 5 in US-East Coast, the total time in ports is (5 x 18.9 hours + 5 x 24.9 hours).

Europe-South Am.	36%	28%	-22%	17%	21	15.6	-26%
North Am.-South Am.	37%	32%	-14%	-5%	21.1	16.8	-20%
Mean/Total	32%	26%	-19%	12%	**20.9**	**16.4**	-22%

* From Table 1

4.4 Fuel efficiency at sea and in port

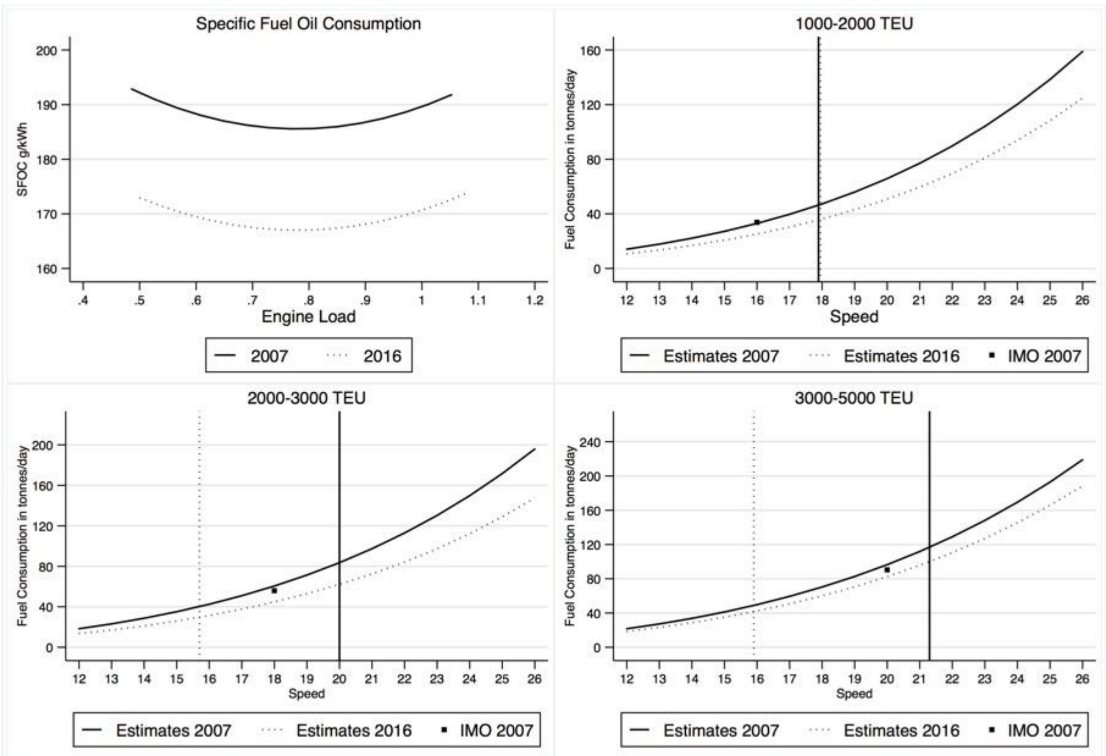
To determine the average fuel consumption in tonnes per day when the vessel is at sea (F) and when in port (G), we use previous information on service characteristics (vessels size and commercial speed) and we rely on data on the engine power in kW and on the design speed (S_{ds}) reported by containership size by IMO (2014) and MAN (2013) for vessels operating respectively in 2007 and in 2016. The 2012 values on design speed and engine power were used for vessels of more than 12 000 TEU as these numbers were not representative for 2007 in IMO (2014).

For both sources, information was used for 7 categories of containership size[2]. The Specific Fuel Consumption is set at 185 g/kWh in 2007 when the engine load is at 80% ($SFOC_{base}$) and changes with engine load so that $SFOC=SFOC_{base}.(0.455load^2-0.71load+1.28)$ as in IMO (2014). The sea-margin is set at 10% (S_m) and we assume that energy efficiency due to technological advances (mostly engine derating and waste heat recovery systems since 2007 according to MAN, 2014) lead to a 10% decrease in SFOC in 2016 compared to 2007. From the fuel consumption at design speed, we then consider that fuel consumption is a cubic function of commercial speed S_z (quadratic when accounting for distance traveled).

For the auxiliary engine fuel consumption, we use estimates from Tran and Lam (2017) on hourly consumption for vessels at sea (F_A=0.0044/24.TEU^0.4923), in port when manoeuvring (G_1=0.05715.TEU^0.2634) and in port when at berth (G_2=0.0128/24.TEU^0.3295). We further consider the additional consumption related to reefer containers. To do so, we use the general rule of 60% more consumption for a reefer compared to a dry container (BSR 2016). To determine the proportion of reefer containers, we first collected data from Drewry on total container volumes per major trade lane for 2007 and 2016 and the reefer share in the total volume of loaded containers. These figures were combined with data on the average vessel utilization per trade direction (east vs. westbound or north vs. southbound) in order to obtain the share of used reefer slots in TEU as a percentage of total vessel capacity in TEU. This resulted in the average absolute number of used reefer slots in TEU per trade lane and sailing direction. The average reefer-related consumption per trade lane was obtained by multiplying the above figures with the fuel consumption per individual reefer.

[2] For simplicity, we didn't consider here that due to Emission Control Areas (ECAs), the vessel may have to switch to a low sulfur fuel when approaching some areas, which might lead to slightly different CO_2 emission rates.

The next figures present our estimates for the 7 categories of vessels on the SFOC and on the speed-main engine fuel consumption per day at sea in 2007 and 2016. We also report, for the commercial speed given in IMO (2014) in 2007, the fuel consumption per day at sea (dot in Figure 3). The gap between the two curves captures the improvement in technology that can be related either to the decrease in SFOC or to new design speed-engine power ratios. Apart from the smallest vessels' category (1 000-2 000 TEU) that remained around 18 knots, there is a general decrease in commercial speed of around 5 knots whatever the vessels since 2007. For larger vessels (more than 12 000 TEU) the commercial speed is on average around 17-18 knots. Finally, when using the commercial speed reported by IMO (2014) for 2007 (IMO 2007 in figure 3) our estimates, using a cubic relationship from design speed, lead to similar results on fuel consumption for the main engine and per day at sea.



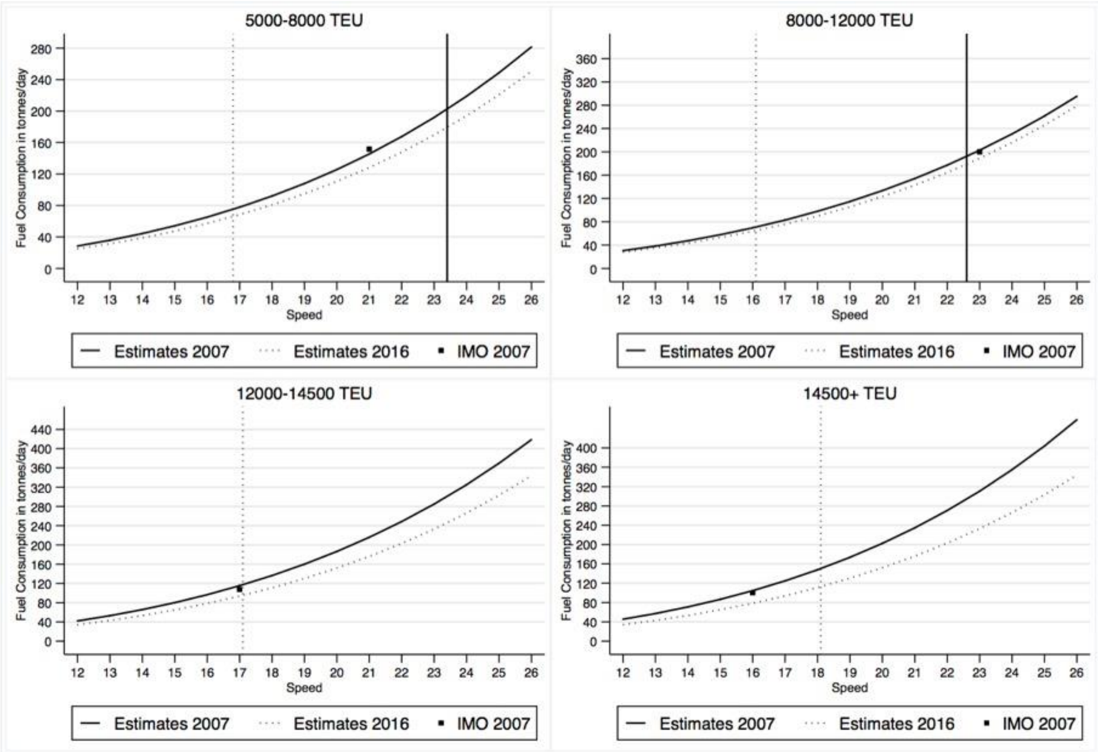


Figure 3. Estimates on main engine fuel consumption per day at sea

5. CO_2 emissions per trade route

Using previous input data, and assuming an emission factor (E_f) at 3.114 g per gram of fuel burned per tons of fuel (IMO 2014), the total amount of CO_2 emitted (equation 1) can be estimated for each trade. Table 5 presents the total emissions per trade, as well as the contribution from the various factors or determinants identified in section 2. For each trade, the total amount of emissions is the sum of emissions estimated for each service deployed in the market (Table 1). The general decrease in annual CO_2 emissions is estimated at 33%. Two factors explain this decrease. First, the CO_2 intensity (-53%) due to the general decrease in speed and change in technology. Second, the decrease in the average distance travelled (-21%). Two factors counterbalance these positive effects, i.e. the increase in the number of vessels (+6%) and the increase in the total deployed fleet capacity, partly due to an increase in the average size of vessels (+71%). In order to estimate these effects, total CO2 emissions were estimated assuming for instance a change in CO_2 intensity, without changing the other parameters. The trade that was subject to the lowest decrease in total emissions is Asia-South America (0.6%) where the impact from the increase in vessel size is the largest (+153%) and counterbalancing the positive impact from CO_2-intensity (-59%).

Table 5. Annual CO_2 emissions in 2007 and 2016 per trade route

	CO_2 Total (in 000)				

Trade	2007	2016	Evol*	Impact from CO2 intensity (a)	Impact from Number of vessels (b)	Impact from TEU deployed (c)	Impact from Distance in nm (d)
Asia-Africa	6 172	4 324	-30%	-53%	16%	60%	-20%
Asia-Europe	52 777	37 917	-28%	-62%	23%	94%	-21%
Asia-North Am.	48 764	28 340	-42%	-50%	11%	32%	-21%
Asia-South Am.	10 028	9 799	-2%	-59%	11%	153%	-15%
Europe-Africa	2 895	1 541	-47%	-39%	-23%	48%	-24%
Europe-N. Am.	15 163	9 017	-41%	-47%	2%	35%	-19%
Europe-S. Am.	6 708	4 452	-34%	-56%	17%	70%	-25%
North Am.-S. Am.	5 048	3 076	-39%	-54%	-5%	75%	-20%
Total	**147 555**	**98 466**	**-33%**	**-53%**	**6%**	**71%**	**-21%**

* Evol=((1+a)(1+b)(1+c)(1+d))-1

Table 6 reports our estimates on average emissions intensity (in grams per TEU-km) at the trade level in 2007 and 2016 and those from the BSR Clean Cargo Working Group (2017) available for 2009 and 2016. Our estimates include the additional consumption of auxiliary engines proportional to the number of reefer container transported, while BSR only reports information for dry or reefer containers separately. The average emission per TEU-km in 2016 is 58 g per TEU-km against 50 for BSR (2016). Our estimates change according to each market with the share of reefer containers transported. The largest emissions are for Europe-Africa with 73 grams per TEU-km on average.

Estimates in 2007 are larger than BSR estimates for 2009 (123 against 81-107 g for BSR 2009). However, the results remain difficult to compare for 2007 for two main reasons. First, slow steaming has been implemented since 2008 and the values used by BSR are probably for lower speeds. Second, BSR estimates in 2009 were based on data from 13 shipowners representing 60% of the capacity deployed (compared to 20 shipowners in 2016 and 80% of capacity), while our sample is for all shipowners deploying weekly services on the main container trade routes. Finally, there was a general improvement in CO_2 emission intensity of 53% since 2007, the largest increase being reported for the Asia-Europe (-62%) and Asia-South America (-59%) trades.

Table 6. CO_2 emissions intensity in g/TEU-km per trade route

Trade	Reefer share	2007 BSR 2009	2007 BSR 2009 reefer	2007 Our estimates	2016 BSR 2016	2016 BSR 2016 reefers	2016 Our estimates	Evol. 2016/2007
Asia-Africa	6%	84	110	112	52	88	52	-53%
Asia-Europe	5%	67	95	105	36	68	40	-62%
Asia-North Am.	7%	76	97	104	48	77	52	-50%
Asia-South Am.	13%	80	104	136	42	73	56	-59%
Europe-Africa	10%	88	122	121	57	94	73	-39%
Europe-N. Am.	9%	82	100	128	52	85	68	-47%
Europe-S. Am.	19%	88	114	130	51	85	57	-56%
North Am.-S. Am.	9%	85	112	149	60	94	69	-54%

Mean	**10%**	**81**	**107**	**123**	**50**	**83**	**58**	**-53%**

To further understand the determinants of the decrease in CO_2 intensity, Table 7 shows the impact from the increase of vessel size, from the decrease in commercial speed and from the reduction in port time for each trade. To do so, we re-estimated the CO_2 intensity assuming for each trade that the same vessel size was used in 2016 and 2007, then the same commercial speed in 2016 and 2007 and finally the same time at sea in 2016 and 2007. As presented in Table 7, on average the 53% change in CO2 emissions intensity is equally explained by the increase in vessel size (-34%) and by the decrease in commercial speed (-35%). However, some disparities exist. On the Asia-North America services, the decrease in CO_2 emissions intensity (-50%) is mostly explained by the reduction of commercial speed (-47%), while on the Asia-South America trade, it is mostly through the increase of vessel size (-44%).

Table 7. Determinants of changes in CO_2 emissions intensity per trade route

	Impact from size & technology (a)	Impact from commercial speed (b)	Impact from network design (c)	Impact from time at sea/in port (d)	Evol. CO_2 intensity 2016/2007*
Asia-Africa	-33%	-34%	-24,6%	38%	-53%
Asia-Europe	-43%	-39%	-22,4%	39%	-62%
Asia-North Am.	-20%	-47%	-30,5%	58%	-50%
Asia-South Am.	-44%	-28%	-21,8%	25%	-59%
Europe-Africa	-37%	-32%	-15,4%	35%	-39%
Europe-N. Am.	-32%	-32%	-11,7%	27%	-47%
Europe-S. Am.	-23%	-33%	-22,4%	-2%	-56%
North Am.-S. Am.	-42%	-36%	-13,9%	33%	-54%
Mean	**-34%**	**-35%**	**-20,3%**	**31%**	**-53%**

* Evol=((1+a)(1+b)(1+c)(1+d))-1

6. Policy and Managerial implications

This research delivers some policy and managerial contributions and policy implications.

First, the research objectives can only be met by constructing a large and detailed database on the global container shipping network allowing a longer-term comparison (2007-2016) of fleet composition, operational characteristics of the fleet such as vessel speed, port factors such as the detailed and analytical measurement of ship turnaround time in ports, etc.

Second, the analysis presented in this paper demands a reliable measurement of the (positive/negative) impact of some contributing factors on the longer term variation of CO_2 emissions. We do not only identify the factors and actors driving changes in the CO_2 emissions, but we also assess their relative contributions to the observed emission changes. The paper shows that policy that focuses on providing incentives for technological changes in the maritime industry has a significant impact as this factor has led to a 53% decrease in global emissions and is the main factor explaining the general decrease in total emissions (33% from Table 5). The paper also stresses that, port managers and terminal operators can have a significant impact on carbon emissions as port time directly plays on the speed at sea that has induced a 35% reduction in emissions (Table 7) from 2007 to 2016.

Third, the findings can be incorporated in numerous studies on liner shipping network design but also into studies on the intermodal hinterland network design problem such as for instance Bouchery et al. (2015). The analysis can be easily disaggregated at a port level to incorporate the choice of port/carrier. For instance, Table 8 reports the average grams per TEU-km emissions when importing or exporting a container to/from Shanghai from some of the largest European ports. Differences amongst ports are mostly explained by the differences in the characteristics of services offered (size of vessel, commercial speed…). It shows that since 2007, there was a general decrease in emissions per TEU of 64% and that Northern and Southern European ports have been subject to a similar decrease. Furthermore, due to shorter distances, the total emissions are lower when importing/exporting from a South European port (616 versus 717 grams), a figure that should be used in conjunction with door-to-port inland-emissions to decide on which port to select from a low carbon point of view. The outcomes as reported in Table 5 to 8 can therefore represent a practical guide to shippers when choosing carriers or ports.

Table 8. Average CO_2 intensity from a selection of European Ports to Port of Shanghai

	2007			2016			Evol. 2016/2007
	Service #	Grams CO_2 TEU -km	Total kg CO_2	Service #	Grams CO_2 TEU -km	Total kg CO_2	
Antwerp	5	98	1906	11	37	718	-62%
Bremerhaven	2	115	2287	9	40	787	-66%
Hamburg	14	108	2150	21	36	709	-67%
Rotterdam	7	102	1979	24	37	711	-64%
Le Havre	5	91	1743	13	38	726	-58%
Zeebrugge	2	104	2008	3	34	650	-68%
North Europe	**35**	**103**	**2012**	**81**	**37**	**717**	**-64%**
Barcelona	8	113	1848	6	41	677	-63%
Genoa	5	120	1920	5	39	620	-68%
La Spezia	3	89	1418	4	35	560	-61%
Valencia	9	103	1706	7	36	592	-65%
Marseille-Fos	4	108	1748	5	39	633	-64%
South Europe	**29**	**107**	**1728**	**27**	**38**	**616**	**-64%**

Finally, our findings show that changes in the maritime component of global supply chains have led to a general decrease in emissions, which are of course beneficial to importers and exporters. For example, consider a hypothetical case of a large retailer importing around 500

000 TEU on average per year over the period from Shanghai to Los Angeles (10 500 km). The decrease from 104 to 52 g/TEU-km (Asia/North America from Table 6) translates into a reduction of the carbon footprint linked to the maritime segment in the retailer's global supply chain from 546 000 tons of CO2 in 2007 to 273 000 tons in 2016. Additional measures could be assessed using our findings when assuming that shippers change the shipment frequency or shipment size (Tang et al., 2015; Liotta et al., 2015). Finally, network design has an important impact on the carbon footprint of container shipping (-20.3% decrease of CO_2 intensity from Table 7) showing that shippers or their logistics service providers can have a significant impact on global carbon footprint by reorganizing global supply chains, with specific focus on the maritime dimension.

7. Conclusions and further research

This paper tempted to achieve a better understanding of the carbon footprint associated with the maritime segment of global container supply chains. Although the initiatives by (manufacturing) firms to mitigate carbon emissions in international markets were recognized by scholars, limited attention has been directed to the reduction that could be achieved from a supply chain and logistics perspective (Tiwary et al., 2015). The selection of the appropriate maritime transport supplier (i.e. the ocean carrier) and the optimal maritime shipping route are key decisions to be made by shippers and logistics service providers in view of an overall carbon emission reduction in global supply chains. This study identified the key factors contributing to CO_2 emissions by container shipping on a worldwide scale and measured the evolution of the total CO_2 emissions in the past decade by offering multi-trade comparisons. In addition, we captured temporal dynamics by analysing to what extent the sample factors contributed to the observed changes in CO_2 emissions in two different years (2007 versus 2016).

This paper contributes to extant academic literature in a number of ways. First, it provides a strong empirical base for the measurement of CO_2 emissions in shipping by relying on unique data on liner service characteristics from various reliable sources, also including the energy consumption for reefer trade, the technological advance in vessel and engine propulsion as well as the increase in port productivity. Second, we propose an original methodology that contemplates the calculation of CO_2 emissions in ports (e.g., approach and maneuvering times, handling operations, etc.), thereby bridging a gap in extant literature. Third, the findings provide empirical evidence on the main drivers of CO_2 emissions. The general decrease in annual CO_2 emissions (about 33%) was mostly driven by CO_2 intensity (-53%), due to the general decrease in speed and technological change, and by the decrease in the average distance travelled (-21%). Fourth, the analysis demonstrated that such changes are trade-dependent and that individual factors contributed in different ways to variations in CO_2 emissions. The Asia-South America trade (0.6%) was subject to the lowest decrease in total emissions, whereas

Europe-Africa and Asia-North America trade lanes recorded the strongest decrease.

In addition, the study offers relevant insights for practitioners and policy makers. Incentives for technological change in the maritime sector are expected to heavily contribute to lower global emissions. The paper also emphasized the role played by port and terminal executives in reducing port time, i.e. a factor that has a significant impact on the reduction of CO_2 emissions. Future research could focus on specific shippers, for instance from the retailer industry or from fresh products industries to further investigate how their global supply chains could be changed when considering emissions at a door-to-door level. Additional studies could also be done at the port level, towards the definition of a Port-to-Port CO_2 efficiency index that could be used by policy makers and practictioners to promote low carbon global supply chains.

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