"Liner Ship Fleet Deployment Model Under Varying Cost of Time: A Bi-criterion Formulation"

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ABSTRACT

Because of decreasing product lifecycles, cost of obsolescence and stock-outs for the final consumers, the value of time in maritime transport is under permanent scrutiny. Time is a determinant factor in the logistics of the globalized production. Any delay in one of the supply chain intermediate steps can lead to bottlenecks affecting the production and/or distribution of goods and consequently, the time needed to reach markets. Therefore, the consideration of the time perspective is essential to any attempt of maritime logistics modelling. In this paper, a liner ship fleet deployment (LSFD) model is applied to a set of transoceanic routes connecting the port of Shanghai, as the only departure point in China, with several ports of the East and West coasts of North America, simulating the weekly containerized traffic between China and USA. The US West Coast ports act as transshipment hubs via the intermodal US rail system and/or the maritime routes to the East coast traversing the Panama Canal. Several shipping lines operate both the Trans-Pacific and Trans-Canal routes with different ships. The rail system is included with specific adaptations to the railways cost structure. We calculate the trade-off between shipping costs and transit time. Using the opportunity cost of time estimated in other studies, we identify the optimal combination of cost and transit time in terms of generalized costs for the importer. Our model assesses the impact of delays from various problems in the ports of the US coast in the China-US trade using a bicriterion formulation.

Liner Ship Fleet Deployment Model Under Varying Cost of Time: A Bi-criterion Formulation

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Abstract

Because of decreasing product lifecycles, cost of obsolescence and stock-outs for the final consumers, the value of time in maritime transport is under permanent scrutiny. Time is a determinant factor in the logistics of the globalized production. Any delay in one of the supply chain intermediate steps can lead to bottlenecks affecting the production and/or distribution of goods and consequently, the time needed to reach markets. Therefore, the consideration of the time perspective is essential to any attempt of maritime logistics modelling. In this paper, a liner ship fleet deployment (LSFD) model is applied to a set of transoceanic routes connecting the port of Shanghai, as the only departure point in China, with several ports of the East and West coasts of North America, simulating the weekly containerized traffic between China and USA. The US West Coast ports act as transshipment hubs via the intermodal US rail system and/or the maritime routes to the East coast traversing the Panama Canal. Several shipping lines operate both the Trans-Pacific and Trans-Canal routes with different ships. The rail system is included with specific adaptations to the railways cost structure. We calculate the trade-off between shipping costs and transit time. Using the opportunity cost of time estimated in other studies, we identify the optimal combination of cost and transit time in terms of generalized costs for the importer. Our model assesses the impact of delays from various problems in the ports of the US coast in the China-US trade using a bicriterion formulation.

Keywords: Fleet deployment, Liner shipping, MIP, Railway traffic, Value of time

1. Introduction

The world merchandise trade is dominated by China that was in 2018 the world leading exporter (2,487 US$ billion) and the second importer (2,136 US$ billion) after the United States (WTO, 2019). Regarding the importance of maritime transport in the merchandise trade, suffice it to say that in 2018 were loaded a total of 11 billion tons of cargo, including 3,2 billion tons of oil and gas and 7,8 billion tons of dry cargo. Containerized traffic accounted for 24% of the dry cargo amounting 1,88 billion tons (Unctad, 2019), highlighting the crucial role that container shipping plays in modern supply chains.

Supply chains are -by definition- related to the geographic dispersion of different locations (Stock *et al.*, 2000) and the corresponding distances between them. The time needed to cover those distances, this is, how long the transport process along the chain takes and at which cost, are one of the main concerns of the supply chain stakeholders. With a focus on the China-US transoceanic supply chains, we approach in this paper the problem from a twofold perspective, the costs incurred by the transport operator and the customer preferences regarding transit time, separating the interests of the transport operators from the customers concerns. The outcome of our simulation is not to find an integrated management decision taken by a single decision-maker, but to highlight the conflict between the carrier and the final customer interests.

The paper comprises a description of the liner shipping industry and an assessment of customers' time perception in Sections 2 and 3. Relevant literature is reviewed in Sect. 4. Sect. 5 analyses the research question that is modelled in Sect. 6. The simulation characteristics are included in Sect. 7. In Sect. 8 the time is introduced, obtaining the corresponding results. Section 9 is dedicated to the conclusions and possible further research.

2. Liner shipping

Although the maritime transport is a highly heterogeneous activity, the shipping industry is mainly based on three different operational approaches: tramp, industrial and liner shipping (Lawrence, 1972). Whereas tramp traffic (that operates to fulfill specific demands) and industrial shipping (mainly related to in-house traffic) both work with a high grade of flexibility, liner shipping operates on a regular basis involving fixed schedules, defined port itineraries and publicized prices. With a strong association to the container traffic, liner shipping is a crucial factor on the economic globalization, playing a fundamental role in the international trade as a main component of the transoceanic supply chains. In 2018 the global containerized trade grew at a 2.6% rate, reaching 152 million Teu's and following the sustained growth tendency (5.8% on average) recorded in the last 20 years (Unctad, 2019).

Liner shipping companies operate on a market structure that implies a global scheme with prices normally made known well in advance, even when the wide scope of the shipping lines client's portfolio can lead to possible price agreements depending on the characteristics of each client, especially regarding traffic volumes. Regularity and compliance with the schedule are crucial factors in liner shipping operations and both are strongly dependent on port performance. To plan the schedule is one the most important elements of the liners decision making process and highlights the network-based character of the industry. Network optimization is a crucial operational factor for the companies, involving three different categories of problems: optimal routing and container flow, optimal design of the network, and efficient fleet operation (Tran and Haasis, 2015). Due to the fixed schedule and defined routing, the efficiency of the operations of any fleet is directly linked to the number and type of ships that must be deployed in each route to minimize the costs. This, tied to the fact that shipping companies redeploy its fleets every 3-6 months to adapt the offer of slots to the demand (Shuaian Wang & Meng, 2012), is the essence of the liner ship fleet deployment (LSFD) problem.

3. The role of time

Historically it has been considered that the demand for maritime transport is derived from the demand for goods. However, the trade globalization and the preeminence of the global supply chains has led to consider that the demand for maritime transport is not only a consequence of the necessity of goods, but an integrated process in which how the customer receive those goods in terms of time and cost, plays a role too (Panayides, 2006). Time along the supply chain arises then as one of the main dimensions in the process of getting the goods from the producers to the hands of the final consumers. As a natural consequence, time to reach the market strongly influences trade flows, acting either as a trade barrier or affecting trade volume (D. L. Hummels & Schaur, 2013). How time acts as a trade barrier can be referred to three dimensions of time: lead time, just in time and time variability. In uncertain demand environments a long lead time -strongly related to transport time in many cases- can have a negative influence on the stock levels leading to either run outs or oversupplies depending on the demand estimations. Time variability on the other hand, is strongly constrained by the cost of the buffer stocks especially when it comes associated to just in time systems, compromising the competitiveness of a supplier even if it is able to deliver goods in a short time (Nordås, Pinali, & Grosso, 2006).Time as a trade cost has been studied among others by (D. Hummels, 2001) who found -using data of a period of 25 years- a 16% tariff rate for the average time (20 days) of imports to USA.

4. Relevant literature

Containership routing and scheduling problems at the strategic, tactical and operational planning levels are reviewed by Meng *et al.*, (2014), including a detailed evaluation of papers regarding fleet deployment models at the tactical level. Liner shipping is a network-based industry, therefore, network decisions play an important role for the liners operation managers. Tran and Haasis, (2015) conducts a literature survey dealing with network optimization decisions in container liner shipping dividing the problem in three main categories: container routing, fleet management and network design. Liner ship fleet deployment (LSFD) have been extensively studied in the last years. Wang and Meng, (2012) emphasize the importance of transshipment in the LSFD problem. They propose a problem formulating a MIP model in which any amount of transshipment operations is permitted in any port. The number of transshipped containers is implicitly represented by origin-based container flow variables substantially reducing the number of required variables. An extended formulation of this model is applied to the numerical simulations of this paper. Meng and Wang, (2012) treats the dual problem linking the tactical level fleet deployment problem to the operational level container routing problem. Wang, (2013) incorporates to the dual problem additional elements as slot-purchasing, type of containers and ships and empty containers repositioning, developing a MILP model including these elements, relaxing the number of transported containers as continuous variables. A fleet deployment problem involving cargo transshipment, multiple container routing options and uncertain demand is proposed by Wang and Meng, (2010), formulating the problem as a stochastic program with an objective function maximizing the expected profit. Initially a sample average estimate is derived from a random sample in order to approximate the objective function, solving then the resulting deterministic program, repeating the process with different samples until a candidate solution is obtained. The same type of problem is proposed by Meng *et al.*, (2012) but including in the deployed fleet not only the liner owned ships but charters ships from other liners.

The existing mathematical models for the treatment of the container liner fleet deployment (CLFD) problem are reviewed by Wang and Meng, (2017), including container transshipment and routing, uncertain demand, empty container repositioning, ship sailing speed optimization and ship repositioning. In that review, fleet deployment with container transshipment and routing models are extensively analyzed, including path-based and origin-destination-link-based fleet deployment models. The origin-link-based fleet deployment model -used in this paper- is equally examined, highlighting the advantage of this model regarding the number of flow variables which is one order of magnitude smaller than in the O-D-link based model.

5. Research question

We analyze the containerized maritime traffic China-USA, combining a maritime and a railway network, considering the later as an extension of the former one. The objective is to minimize the operational costs of both the liner and railway fleets as well as the total transport time required. This bicriterion formulation implies a tradeoff between cost and time: sea transport is cheaper than rail but slower. If the consumer perceives time as an important factor, will be prone to pay more using the rail from coast to coast. On the other hand, if the cost is a priority, sea transport will be the preferred choice. The whole combined network is considered -regarding the costs- as operated by the same liner shipping company, turning the freight rail rates into liner internal costs. Port delays and /or disruptions add additional constraints to the problem.

The deployment of the fleet of a liner shipping company rises the LSFD problem. In the present work, that problem is formulated as a mixed-integer programming (MIP) problem (Shuaian Wang & Meng, 2012) including transshipment. Implicit container flow origin-based variables are used. To make compatible the rail costs with the maritime operations the costs of the rail system are adapted to the shipping liners cost structure. In a first step we carry out a numerical simulation including a single port in China, ports of the US East and West coasts and several US railway nodes as well as the two ports on both sides of the Panama Canal. In a second step we introduce the transporting time.

6. Model

A liner container shipping company operates a network (set R) of ship routes $r \in R$, serving on a weekly basis a defined set of ports $p \in P$. A ship route is represented by its port rotation:

$$p_{r1} \rightarrow p_{r2} \rightarrow \cdots \rightarrow p_{rN_r} \rightarrow p_{r1} \qquad [1]$$

For the route R, the total number of ports of call is N_r (i = 1, 2, …, N_r), the ith port of call is p_{ri} and I_r = {1, 2, …, N_r} is the set of the port indices, defining $I_{rp} \subset I_r$ as the set of port indices referred to a specific port $p \in P$. The routes are cyclical ($p_{r,\mathrm{N}_r+1} := p_{r1}$) and the voyage between the ports p_{ri} and $p_{r,i+1}$ is denoted as the *leg i* of the ship route $r \in R$. This leg can be defined by the pair of consecutive ports (p_{ri}, $p_{r,i+1}$), $i \in I_\mathrm{r}$.

The containers -reflected in the problem as twenty equivalent units (TEU's)- can be loaded, unloaded and transshipped at any port $p \in P$ with the following charges (USD/TEU):

$\bar{c}_p$: Container transshipment cost at port $p \in P$
$\hat{c}_p$: Container loading cost at port $p \in P$
$\tilde{c}_p$: Container discharging cost at port $p \in P$

To be noted that for most of the port operators and in order to encourage transshipment operations, $\bar{c}_p < \hat{c}_p + \tilde{c}_p$. The number of containers d_{od} (TEUs/week) transported between each pair of origin $o \in P$ and destination $d \in P$ ports is considered as the input for the fleet deployment problem. The liner shipping company deploys a fleet (set ϑ) of ships (either all of them owned or part chartered-in) of type $v \in \vartheta$ with the following attributes:

c_v^{opr}: Fixed operating costs (USD/week) of a ship type $v \in \vartheta$. This cost doesn't depend on the number of voyages and includes the cost of the stores, lubricants, fuel for the auxiliary power plant, maintenance, repair, crew and administration.
c_{pv}^{ber}: Berth occupancy charges (USD/h) at port $p \in P$ for a ship $v \in \vartheta$.
Cap_v: The maximum capacity (in TEU's) of a ship $v \in \vartheta$
N_v^{own}: The number of ships of type $v \in \vartheta$ owned by the liner.
N_v^{in}: The maximum number of ships of type $v \in \vartheta$ chartered by the liner.
c_v^{in}: Chartering-in price (USD/week) of a ship type $v \in \vartheta$.
c_v^{out}: Chartering-out profit (USD/week) of a ship type $v \in \vartheta$, ($c_v^{out} < c_v^{in}$, $v \in \vartheta$).

Constraints like the ports and/or canals' physical or geographical characteristics prevent some types of ships from being deployed on some routes. Consequently, a sub-set $\vartheta_r \subset \vartheta$ is defined for the candidate ships that can be deployed on the route $r \in R$. For operational reasons, all the ships deployed on a route $r \in R$ are of the same type $v \in \vartheta_r$ and all of them sail at the same speed. To maintain the schedule, the number of ships to be deployed on a route is dependent on the round-trip time (sailing time plus port operations time). The sailing time -including the pilot time necessary for port entrance and departure- of a ship type $v \in \vartheta_r$

deployed on a leg of a route $r \in R$ is denoted by τ_{rv}^{fix}, defined by its sailing speed that is an input of the model. The time that a ship is berthed for container handling is the port operations time. It is related to the efficiency of the quay cranes at each port, that is the main factor influencing the number of handled containers. Thus, for a ship $v \in \vartheta$, the average time needed for loading/unloading one TEU at a port $p \in P$ is defined by t_{pv} (h/TEU). Provided that the round-trip time of a route depends on the containers handled at the ports of the route, the number of ships (denoted by m_r) deployed on route $r \in R$ necessary to maintain a regular service is a decision variable. The LSFD problem is to determine the type and number of ships that a liner shipping company must charter in and out, the number of ships that must be deployed in the served routes and the number of transshipped containers at the different ports of the network to satisfy the weekly container demand at them, minimizing the total weekly cost. This cost comprises for m_r ships of type $v \in \vartheta$ deployed on a ship route $r \in R$, the chartering and container handling costs plus the operating costs, that can be divided in three parts: the ship related costs symbolized by $m_r c_v^{opr}$ (USD/week), the voyage costs represented by c_{rv}^{fix} (USD/week) -including the fuel cost and the different charges at ports and canals- and the berthing costs, depending on the time berthed and port berthing rates. To model the LSFD problem the authors use the following vector of decision variables:

$$\mathbf{x} = \left(n_v^{in}, n_v^{out}, m_r, x_{rv}, \hat{z}_{ri}^{o}, \tilde{z}_{ri}^{o}, f_{ri}^{o} \middle| r \in R, v \in \vartheta, i \in I_r, o \in P, d \in P, o \neq d\right) \qquad [2]$$

Where,

n_v^{in}: Number of chartered in ships of type $v \in \vartheta$

n_v^{out}: Number of chartered out ships of type $v \in \vartheta$

m_r: Number of ships deployed on route $r \in R$

x_{rv}: Binary variable; 1 if ship route $r \in R$ is deployed with ships of type ($v \in \vartheta_r$); 0 otherwise

$\hat{z}_{ri}^{o}$: Number of containers (TEUs/week) originating from port $o \in P$ and loaded at the ith port of call on ship route R

$\tilde{z}_{ri}^{o}$: Number of containers (TEUs/week) originating from port $o \in P$ and discharged at the ith port of call on ship route R

f_{ri}^{o}: Number of containers (TEUs/week) originating from port $o \in P$ and stowed on board of ships sailing on the ith leg of $r \in R$

Given the vector **x** the problem is formulated as a mixed-integer nonlinear problem. The following vector is added:

$$\hat{\mathbf{x}} = (m_{rv}, z_{riv} | r \in R, v \in \vartheta_r) \qquad [3]$$

where,

m_{rv}: Number of ships of type $v \in \vartheta_r$ deployed on the route $r \in R$

z_{riv}: Total number of containers handled in a ship $v \in \vartheta$ at the ith port of the route r

Thus, the problem is transformed into a mixed-integer linear programming model comprising the costs related to the ships in operation, the voyage costs, the cost of berthing, the transshipment costs and the handling cost, plus the chartering-in costs and the chartering-out profits that in our model are eliminated. To consider the costs of sailing through the Panama Canal we define two new sub-sets: $R_c \subset R$ and $I_{rc} \subset I$. R_c is the set of routes including the Canal and I_{rc} is the set of port indices of the last port of call before the Canal transit in the route $r \in R_c$. In compliance with the Canal rules, a tariff c_{ri}^{canalc} is applied to the number of TEUs on board the ships ($f_{ri}^{o} | \ r \in R_c, i \in I_{rc}$), this is, to the number of containers transiting the Canal; a tariff c_{riv}^{canalv} is equally applied to the ships transiting the Canal according to their capacity in TEUs. For the rail routes, a new sub-set $R_{rl} \subset R$ is defined. The land route distances are expressed in nautical miles (n.m.) and the sailing and running speeds in n.m./h (knots). Due to the different nature of the ship and rail networks, all the rail costs are integrated in a single cost related to the rail voyage. Therefore, fixed operating costs of the trains, berthing costs and the handling and transshipment costs are not included in the rail network. The remaining cost is a rail specific fixed voyage cost ($c_{rv}^{fixrl} | \ r \in R_{rl}, v \in \vartheta_r$).

For the decision vectors [2] and [3] the minimum total weekly cost $TC'(\boldsymbol{x}, \widehat{\boldsymbol{x}})$ of a joint group of liner shipping companies and rail operators, deploying m_{rv} ships and trains of type $v \in \vartheta_r$, on the routes $r \in R$, to attend a weekly demand d_{od}, is:

$$\begin{aligned}
\min_{\boldsymbol{x},\widehat{\boldsymbol{x}}} TC'(\boldsymbol{x}, \widehat{\boldsymbol{x}}) = & \sum_{r \epsilon R} \sum_{v \epsilon \vartheta_r} \left(m_{rv} c_v^{opr} + c_{rv}^{fix} x_{rv} \right) \\
& + \sum_{r \in R_{rl}} \sum_{v \epsilon \vartheta_r} c_{rv}^{fixrl} x_{rv} + \sum_{r \epsilon R_c} \sum_{i \epsilon I_{rc}} \sum_{o} c_{ri}^{canalc} \ f_{ri}^{o} + \sum_{r \epsilon R_c} \sum_{v \epsilon \vartheta_r} \sum_{i \epsilon I_{rc}} c_{riv}^{canalv} x_{rv} \\
& + \sum_{r \epsilon R} \sum_{i \epsilon I_r} \sum_{v \epsilon \vartheta_r} c_{p_{ri}v}^{ber} t_{p_{ri}v} z_{riv} \\
& + \frac{1}{2} \sum_{p \epsilon P} \bar{c}_p \left[\sum_{r \epsilon R_p} \sum_{i \epsilon I_{rp}} \sum_{o \epsilon P} \left(\hat{z}_{ri}^{o} + \tilde{z}_{ri}^{o} \right) - \sum_{d \epsilon P} d_{pd} - \sum_{o \epsilon P} d_{op} \right] \\
& + \sum_{o \epsilon P} \sum_{d \epsilon P} \left(\hat{c}_o + \tilde{c}_d \right) d_{od}
\end{aligned}$$

s.t.

$$\sum_{v \epsilon \vartheta_r} x_{rv} = 1; \qquad \forall r \in R \tag{4}$$

A round trip normally does not take more than 15 weeks. we can set M_1=15 and $M_2 =$ 15weeks x 168 h/week = 2520 h. The sailing time (h) of a ship v on the route r (including standby time for pilotage at the ports) is referred to as τ_{rv}^{fix}:

$$m_{rv} \leq M_1 x_{rv}; \qquad \forall r \in R; \ \forall v \in \vartheta_r \tag{5}$$

$$168 m_{rv} + M_2 (1 - x_{rv}) \geq \tau_{rv}^{fix} + \sum_{i \epsilon I_r} t_{p_{ri}v} z_{riv} \tag{6}$$

The number of containers transported on each leg of each route is constrained by:

$$\sum_{v \epsilon \vartheta} f_{ri}^{o} - \sum_{v \epsilon \vartheta_r} Cap_v x_{rv} \leq 0; \quad (\forall r \epsilon R; \ \forall i \epsilon I_r) \qquad [7]$$

Flow conservation at each port of call:

$$f_{r,i-1}^{o} + \hat{z}_{ri}^{o} = f_{ri}^{o} + \tilde{z}_{ri}^{o} ; \ \forall r \epsilon R; \ \forall i \epsilon I_r; \forall o \epsilon P \qquad [8]$$

$$\sum_{r \epsilon R_d} \sum_{i \epsilon I_{rd}} (\tilde{z}_{ri}^{o} - \hat{z}_{ri}^{o}) = d_{od} ; \quad \forall o \epsilon P; \forall d \epsilon P \qquad [9]$$

Maximum number of handled containers z_{riv}:

$$z_{riv} \leq M_3 x_{rv} \ ; \ \forall r \epsilon R; \ \forall i \epsilon I_r; \ \forall v \epsilon \ \vartheta_r \qquad [10]$$

$$z_{riv} + M_4(1 - x_{rv}) \ \geq \sum_{o \epsilon P} (\hat{z}_{ri}^{o} + \tilde{z}_{ri}^{o}) \ ; \forall r \epsilon R; \ \forall i \epsilon I_r; \forall v \epsilon \vartheta_r \qquad [11]$$

$M_3 = M_4 = 2 \max \{Cap_v\} \ \forall v \epsilon \vartheta$

No return to a port of the containers originating from that same port:

$$f_{ri}^{o}=0; \ \forall r \epsilon R; \ \forall i \epsilon I_r; \quad o = p_{ri+1} \qquad [12]$$

Containers are not discharged at a port if their origin is the same port:

$$\tilde{z}_{ri}^{o}=0; \ \forall r \epsilon R; \ \forall i \epsilon I_r; \quad o = p_{ri} \qquad [13]$$

Decision variables non-negativity and integer attributes:

$$x_{rv} \in \{0,1\}; \qquad m_{rv} \in \mathbb{Z}^{+} \cup \{0\}; \quad \forall r \epsilon R; \ \forall v \epsilon \vartheta_r \qquad [14]$$

$$\hat{z}_{ri}^{o} \geq 0 \ ; \ \tilde{z}_{ri}^{o} \geq 0; f_{ri}^{o} \geq 0 \qquad \forall r \epsilon R; \quad \forall i \epsilon I_r; \ \forall o \epsilon P \qquad [15]$$

$$z_{riv} \geq 0 \ ; \qquad \forall r \epsilon R; \quad \forall i \epsilon I_r; \ \forall v \epsilon \vartheta_r \qquad [16]$$

7. Simulation data, parameters and characteristics

A stylized network of the US railway system (Fig 1) is added to the network of maritime routes:

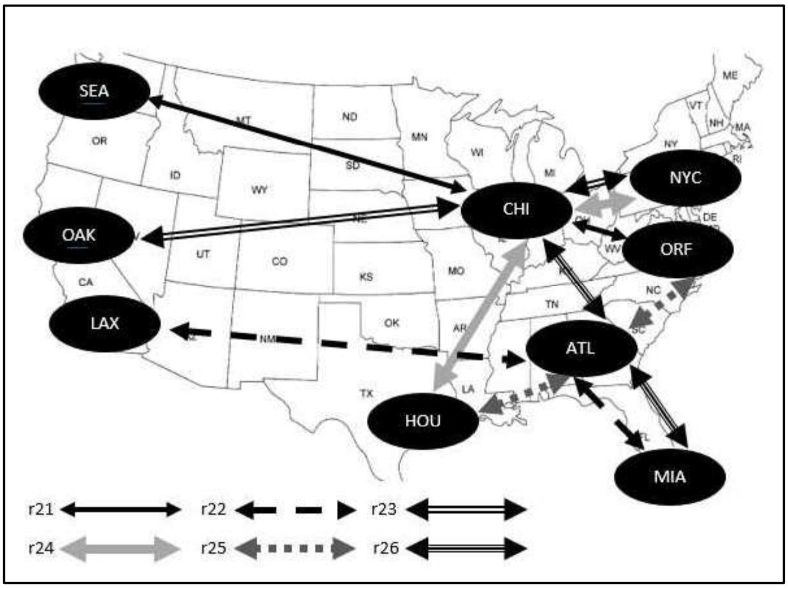

Figure 1. Rail routes

The simulations are carried out with a total export/import traffic China-USA of 194.108 Teu's/week transported at different sailing speeds, mimicking the real trade between China and

USA (Jan-Dec 2017) using data from the USA Census Bureau (https://usatrade.census.gov/). Table 1 displays this weekly demand distributed by ports/ramps:

Ports	SEA	OAK	LAX	HOU	MIA	ORF	NYC	CHI	ATL
Export SHA	5200	20546	20546	17082	4347	9731	21304	16639	14789
Import SHA	5635	9157	9157	8303	2076	7535	8333	6474	7254

Table 1. Weekly demand (Teu's). Total demand :194.108

The traffic demanded or exported by each state is grouped in 8 groups of states and proportionally assigned to the nearest port, except for the group of California that is assigned to two ports (OAK and LAX). The ports at both ends of the Panama Canal (BLB and MIT) are included only as transshipment ports (cero demand). Five types of ships are considered with different capacities plus a train type assimilated to a ship in Table 2:

Ship Code	v1	v2	v3	v4	v5	v6
Type	Ship	Ship	Ship	Ship	Ship	Train
Capacity (TEUs)	5000	8000	10000	12000	18000	5600
Considered speed range (Knots)	20-24	20-22	18-22	16-18	16	40
Fixed oper. cost c_v^{opr} (USD/week)	70000	80000	90000	105000	130000	*
Fixed call of ports cost (USD)	7000	9000	10500	12000	16000	*
Berthing charge (USD)	1500	2100	3100	3900	4900	*
Fixed time port entrance (h)	4	4	4	4	4	4
Container handling time (h/TEU)	0,01	0,008	0,008	0,007	0,006	0,02

Table 2. Fleet characteristics

The voyage cost per route (c_{rv}^{fix}) and the sailing/running time (τ_{rv}^{fix}) are calculated for both the maritime (Table 3) and rail (Table 4) routes:

Ships		*Routes*		
		r11	r12	r13
v1	c_{rv}^{fix}	1.225.600,00	2.602.261,82	1.381.390,00
	τ_{rv}^{fix}	616,00	1.088,36	485,29
v2	c_{rv}^{fix}	1.332.000,00	2.799.261,38	1.299.351,71
	τ_{rv}^{fix}	616,00	1.088,36	524,32
v3	c_{rv}^{fix}	1.242.000,00	2.652.168,00	1.355.558,18
	τ_{rv}^{fix}	682,67	1.191,60	524,32
v4	c_{rv}^{fix}	1.163.400,00	2.444.142,22	
	τ_{rv}^{fix}	766,00	1.317,78	

v5	c_{rv}^{fix}	1.277.800,00		
	τ_{rv}^{fix}	766,00		

Table 3. Maritime routes (in n.m.). Voyage cost c_{rv}^{fix} (USD) and voyage time τ_{rv}^{fix} (h)

			Routes			
V6	r21	r22	r23	r24	r25	r26
	5.532	5.924	5.780	3.820	3.168	2.598
c_{rv}^{fixrl}	12.001	12.861	12.548	8.293	6.877	5.640
τ_{rv}^{fix}	154,30	164,10	160,50	111,50	95,20	80,95

Table 4. Rail routes (in n.m.). Voyage cost c_{rv}^{fixrl} (kUSD) and voyage time τ_{rv}^{fix} (h)

Three maritime routes are considered:

r11 SHA-SEA-LAX-OAK ► SHA
r12 SHA-BLB-NYC-ORF-HOU-MIT ► SHA
r13 OAK-BLB-MIA-HOU-MIT-LAX ► OAK

The possible disruptive effects (delays) are focused at the ports of the US Pacific Coast (SEA, OAK and LAX) and the ports of Balboa (BLB) and Colon (MIT) at the Panama Canal. The delays are simulated changing the time required to enter the different ports. The potential troublesome situations (as port strikes) in the US West Coast, increase the total time sailing time and consequently the number of ships required to keep the weekly service, with the corresponding increase of the total cost. Two situations are considered: normal operation and delays at the three ports of US West Coast.

For rail destinations we consider a daily rail service of two "standard" trains/day with a capacity of 400 TEUs each one. To calculate c_{rv}^{fixrl}, the average US freight rail rate (USD/ton-mile.) is turned into a cost per ton and nautical mile, converted into a USD/TEU-n.m. cost and applied to an "equivalent train" Integrating that cost along each rail route, a weekly voyage cost is obtained as in Table 5:

Average US freight rail rate (USD/ton-n.m.)	0,043
Average weight of a TEU (tons/TEU)	9
Equivalent (14 trains/week) train capacity (TEUs)	5.600
$\boldsymbol{c_{rv}^{fixrl}}$/ equivalent train-n.m. (USD)	2.171

Table 5. Rail parameters

The maritime routes sailing time (τ_{rv}^{fix}) includes the time necessary for port entrance ($t_{r,i}^{fix}$):

$$\tau_{rv}^{fix} = \sum_{r\epsilon R}\sum_{i\epsilon I_r}\sum_{v\epsilon\vartheta_r} t_{r,i}^{fix} + p_{ri}^{dis}/s_{rv}^{spd} \qquad [17]$$

$t_{r,i}^{fix}$ is set to 4 h for all the ports except the Canal entrance ports. Since the model fixes the sailing speed for all the legs of each route, the sailing speed along the Canal legs cannot be reduced. Considering an entrance time $t_{r,i}^{fix}$ of 20 h in the canal entrance ports, the Canal traversing speed is compensated to mimic the real one that is always much lower than the cruise speed.

8. Introducing time and results

To consider the time needed to ship all the containers between China and the US, two additional terms are considered:

$$T_{ri}^{leg} = \sum_{r\epsilon R}\sum_{i\epsilon I_r}\sum_{v\epsilon\vartheta_r}\sum_{o\epsilon P}(t_{r,i}^{fix} + p_{ri}^{dis}/s_{rv}^{spd})f_{r,i-1}^{o} \qquad [18]$$

$$T_p^{trans} = \frac{1}{2}\sum_{p\epsilon P} t_p^{trans}\left[\sum_{r\epsilon R_p}\sum_{i\epsilon I_{rp}}\sum_{o\epsilon P}(\hat{z}_{ri}^{o} + \tilde{z}_{ri}^{o}) - \sum_{d\epsilon P} d_{pd} - \sum_{o\epsilon P} d_{op}\right] \qquad [19]$$

T_{ri}^{leg} defines the total product of the corresponding number of containers on board on each leg of every route r times the sailing time of that leg (in TEUs-hour). Each element of the time-flow expression [18] consequently refers to the time that the containers are sailing the leg $\mathrm{p_{ri-1}}$- $\mathrm{p_{ri}}$ of the route r on board the ships (including the time to enter the ports). T_p^{trans} corresponds to the total product of the number of transshipped containers at each port times the estimated average time of the transshipment operations (in TEUs-hour). Each element of the time-transshipment expression [19] therefore refers to the time that the total number of transshipped containers are waiting at each port for transshipment. The estimated average time of transshipment denoted as t_p^{trans} is set to 3.5 days.

To simulate the relative importance of cost and time we add terms [18] and [19] to the objective function. We then obtain a bicriterion function $\mathrm{L}_n(\boldsymbol{x},\widehat{\boldsymbol{x}})$ representing the total cost and the transportation time, respectively. Since the two criteria do not necessarily correspond to a single well-defined decision maker using a unique cost of time, we use convexification of the bicriterion function in [20] to calculate the efficient frontier for a range of preferences, ranging from a pure cost minimization (the liner's perspective, $\alpha_n = 0$, to pure time minimization (the end customer perspective), $\alpha_n = 1$.

$$\mathrm{L}_n(\boldsymbol{x},\widehat{\boldsymbol{x}}) = (1-\alpha_n)TC'(\boldsymbol{x},\widehat{\boldsymbol{x}}) + \alpha_n\left(T_{ri}^{leg} + T_p^{trans}\right) \qquad [20]$$

$$0 \le \alpha_n \le 1; \quad n = 0 \ldots 10 \quad (\alpha_n = 0.1 * n)$$

The efficient frontier is naturally producing a substitution between the operating cost and the minimum time for the optimal choices. The lower the time involved in shipping the reference number of TEUs, the higher the operating costs are. On the other hand, the only way to reduce total operating costs consists in accepting that the containers stay longer on the way.

The described trade-off depends on many of the parameters of the model like average speed, berth occupancy charges, port-entry times etc. Since we want to simulate the impact of delays on the entry harbors at the West Coast of the US, the shocks considered are implemented carrying out four consecutive sets of iterations with different port-entry times. The first set corresponds to the normal situation: 4 hours to enter each port (including pilotage) except for the two Panama Canal entry ports (BLB and MIT) in which -as already stated- the entry-port time is 24 hours to compensate the slow speed during canal sailing. For the other three consecutive sets, the entry-port time at the US west coast ports is set to 168, 336 and 504 hours, (one, two or three weeks), remaining the rest of ports as in set one.

The efficient bicriterion frontier or tradeoff curve is illustrated in Fig 2 for four different delay scenarios. At the benchmark curve (4 h delay), reducing the cost from 305 mill. USD (11^{th} iteration) to 172 M USD (10^{th} iteration), implies increasing total time from 85 to 89 mill. of hours needed to transport the total amount of TEUs considered (194.108). To be noted that this model reassigns the whole intermodal traffic shifting between train and ship, and among different shipping routes, in each of the iterations considered. The curves show an asymptotic behavior at the extremes. At some point the marginal cost of a time reduction will exceed the perceived willingness to pay of the customer. Increasing port-entry times shifts these curves away from the origin, showing that similar costs as in the benchmark can only be achieved at the expense of an increase in the total number of hours. Similarly, keeping the benchmark time implies an increase in total operating costs.

Beyond the general use of the formulation to address an arbitrary mix of goods, we can also provide a numeric estimate for the average value in a realistic setting. To capture the monetary value of the customer perception of time we draw on data in Hummels (2001) and Hummels and Schaur (2013). Departing from the modal choice of firms between air and maritime transport, Hummels and Schaur (2013), use timely delivery as an element identifying quality differentiation in trade. They end up estimating a parameter that allows translating delays in days into a price equivalent form. This parameter shows the increase in costs due to an extra day increase in delivery time from the second day onwards. The ratio between cost and the value of the goods shipped allows the calculation of this cost in a tariff equivalent form.

We calculate a weighted average of the tariff equivalents of all the goods imported from China to the different US (continental) states. Following the national distribution pattern, we calculate the composition in Tons of a “standard” Teu, resulting in a value of 44.439,4 USD. The final composition of each TEU mimics the average yearly composition of US imports from China. Finally, we apply the corresponding tariff equivalent (Hummels and Schaur) to the values by component/type of good. The sum of all these values represents the value of each day of delay by TEU (288 USD).

The resulting average tariff equivalent is 0.65%, which means that each additional day in transit is equivalent for the importer to imposing a 0.65% ad-valorem tariff to the average value of each TEU. The slope of the generalized costs line is derived from this average tariff equivalent and implies that the importer is ready to pay 288 USD for the reduction of one day in transit. We can use now this average tariff equivalent to identify which of the feasible combinations between sailing time and cost is optimal for the importer. This optimal combination would correspond to the one with the minimum generalized cost for the users.

In Figure 2, the iso-cost curves for each delay scenarios are based on the empirical assessment for the US importers' value of time perception. This allows determining the optimal solution as the tangential point between the iso-cost curve and the efficient bi-criteria frontiers already derived in Figure 2. Note that the iso-cost curve is derived for the importer's valuation whereas the bicriterion formulation expresses the overall cost impact of liner operations, import and export.

For the initial delays in the US East Coast ports, importers would be ready to accept higher total delays to avoid high cost increases. However, for subsequent delays, users are increasingly ready to support higher costs in order to lower the impact on time delays. In fact, importers are ready to accept 5 days of extra delay and an increase is 56 USD per container when increasing the delay from 4 hours to 1 week, but they are only ready to increase the delay in one day while being ready to pay 341.6 USD per container when increasing the delay from one to two weeks. To be noted that an extra week delay, ends up in a reduction of only 0.4 days with a cost increase of 2002 USD/Teu. This is because the higher the delays the better the option of using shipping lines not calling the US East Coast ports. This alternative is cheaper than the train and, after significant delays not necessarily slower.

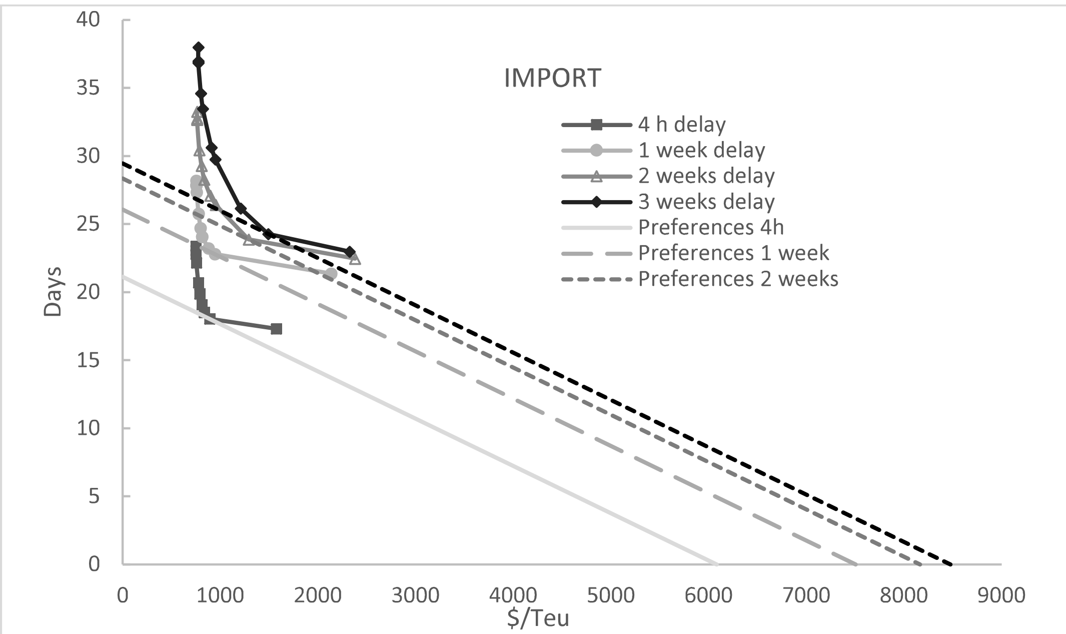

Figure 2. Unitary cost-time tradeoff for import.

Table 6 decomposes the impact of the different delays considered in terms of operating costs and time opportunity cost comparing the different delays to the initial (4 hours delay for entrance in the ports) scenario. The opportunity cost of the increase in the average number of days that the containers are on their way is calculated by multiplying the number of days with the average value associated to the reduction of one day in transit (288 USD), which corresponds to an average tariff equivalent of 0.65%. We have calculated state-specific opportunity costs as the sum of operating cost and time opportunity cost for all states, averaging 0.65% with a minimum of 0.37% (Louisiana) and maximum of 1.16% (North Dakota).

In Table 6 we display the increase in operating costs and the extra delay in days per TEU for each of the delay scenarios. The different increases in the operating costs represent changes between 6,36% and 67.39%. These costs should be confronted by the shipping companies to the costs of solving the origin of the delays, in cases like strikes or other operational or administrative problems at the ports. We obtain the opportunity cost of the increase in days multiplying the extra delay in days by the average opportunity cost per day (288 USD).

Delay (weeks)	Operating cost impact	Increase in days	Opportunity cost impact	Total generalized cost
1	56,66	4,75	1.368,06	1.424,73
2	398,29	5,85	1.685,46	2.083,75
3	600,32	6,24	1.796,57	2.396,89

Table 6. Increases in cost (USD/TEU) associated to the different delays (weeks) considered

Although there is no direct internalization of these costs by the shipping companies, the readjustments in the use of the different transport modes and routes can be considered a response to the pressure to reduce costs and time by the clients. Should the origin of the problem need the response of the public administration, like in cases of infrastructure damages due to terrorist attacks or natural disasters, the decisions of the public sector should consider those weekly total generalized costs.

9. Conclusions

The value that the customer assigns to delivery time plays an important role in the transport mode selection, therefore, the incorporation of time in the objective function is a valuable improvement. Shorter product lifecycles, hardened retail competition and impatience in customer preferences are all signs of this tendency.

This double objective, minimizing operating costs and timer allows the calculation of the trade-off between cost and delivery time. Including the time element in the objective function of the LSFD2 we intend to obtain insights into the importer opportunity cost of delivery time and consequently, about the decision-making process concerning the route and mean of transport to be followed by the imported goods. Conventionally, the choice of transport mode or transshipment has been based on cost-minimizing models, which may no longer fully represent the demand development.

Enhancing the liner shipment modelling with time not only creates a link to the contemporary supply chain literature, but it may also lead to improvements in the estimation of marginal transportation flows, utilization rates of infrastructure and forecasting transport pricing. However, we leave these avenues for further research.

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