

MODELLING PERFORMANCES OF THE SUPPLY CHAIN(S) SERVED BY THE MEGA FREIGHT TRANSPORT VEHICLES

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ABSTRACT

This paper deals with modelling of performances of the supply chain(s) served by different including the mega freight transport vehicles. The chain(s) consists of the spoke and hub supplier(s) and the hub and spoke consumer(s) of goods/freight shipments. The considered chain's performances are infrastructural, technical/technological, operational, economic, environmental, and social. The infrastructural performances relate to the characteristics of production, storing, and consumption plants of goods/freight shipments, and transport infrastructure spreading between them. The technical/technological performances reflect characteristics of the facilities and equipment for loading/unloading and storing goods/freight shipments including forms of their consolidation, and the freight vehicles transporting them between the hub supplier(s) and the hub consumer(s). The operational performances include the transport service frequency of goods/freight shipments, , size of deployed transport vehicle fleet, and its productivity. The economic performances embrace the inventory, handling, and transport cost. The environmental performances relate to the energy (fuel) consumption and the consequent emissions of GHG (Green House Gases). The social performances include noise, congestion, and safety (i.e., risk of incidents/accidents). The analytical models for estimating the above-mentioned performances of the generic configuration of supply chain operating according to the specified scenario(s) under given conditions are developed. The models are applied to the intercontinental supply chain exclusively served by the conventional and mega mega container ships aiming at investigating their effects/impacts on the chain's particular performances.

Key words: supply chain(s), performances, analytical models, mega container ships

1 INTRODUCTION

Among numerous definitions of supply chains is as follows; “ A supply chain is a network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers” (Ganeshan and Harrison, 1999). In this paper, the

supply chain is considered as the physical network producing, handling, transporting, and consuming goods/freight shipments consolidated into TEUs (Twenty Foot Equivalent Unit(s)). Generally, these goods/freight shipments need to be delivered from the ultimate suppliers to the ultimate customers efficiently, effectively, and safely. The particular ultimate suppliers and customers such as the large production/consumption plants, distribution centers, sea-ports, airports, large surface modal (rail, road), and intermodal (rail/road/barge) terminals usually generate and attract rather substantive flows of these (consolidated) goods/freight shipments. As such, they operate as the hub nodes of the global (continental and intercontinental) freight transport network(s). In many cases, these substantive flows to be transported between particular hub nodes can justify more frequent if not also regular use of larger including the mega freight transport vehicles.

(<http://www.investopedia.com/terms/s/supplychain.asp>;
http://en.wikipedia.org/wiki/Supply_chain.)

In general, the size and payload capacity of the freight transport vehicles operated by different transport modes such as road, rail, air, sea, and intermodal, while serving the variety of supply chains has increased over time. The main driving forces for such increase have been: i) growing volumes and diversity of freight transport demand in combination with its increased internalization, globalization, and consequently the rate of consolidation, i.e., containerization, ii) strengthening competition in the freight transport markets forcing transport operators from almost all modes to permanently improve efficiency, effectiveness, and safety of their services; iii) increasing importance of the economics of freight transport and related logistics, iv) raising concerns on the impacts of freight transport sector and its particular modes on the environment and society, and v) innovative design, materials, and manufacturing processes of the vehicles, supportive facilities and equipment, and infrastructure. Figure 1 shows an example of the relationships between the demand and capacity at the world's maritime container transport (UNCTAD, 2013).

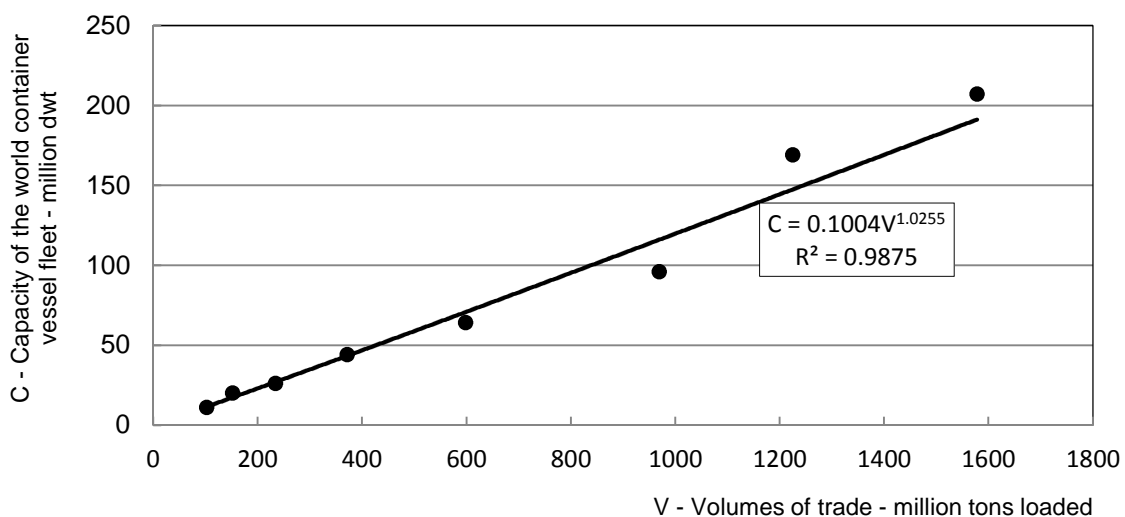


Figure 1 Relationships between the containerized freight volumes of seaborne trade and the capacity of container ship fleet (period 1980-2013) (UNCTAD, 2013)

As can be seen, the capacity of the world's container fleet has been increasing more than proportionally driven by the need for satisfying growing goods/freight containerized volumes

of demand during the observed period (1980-2013). In addition, the average size of the ordered container ships has also been increasing over time as shown in Figure 2.

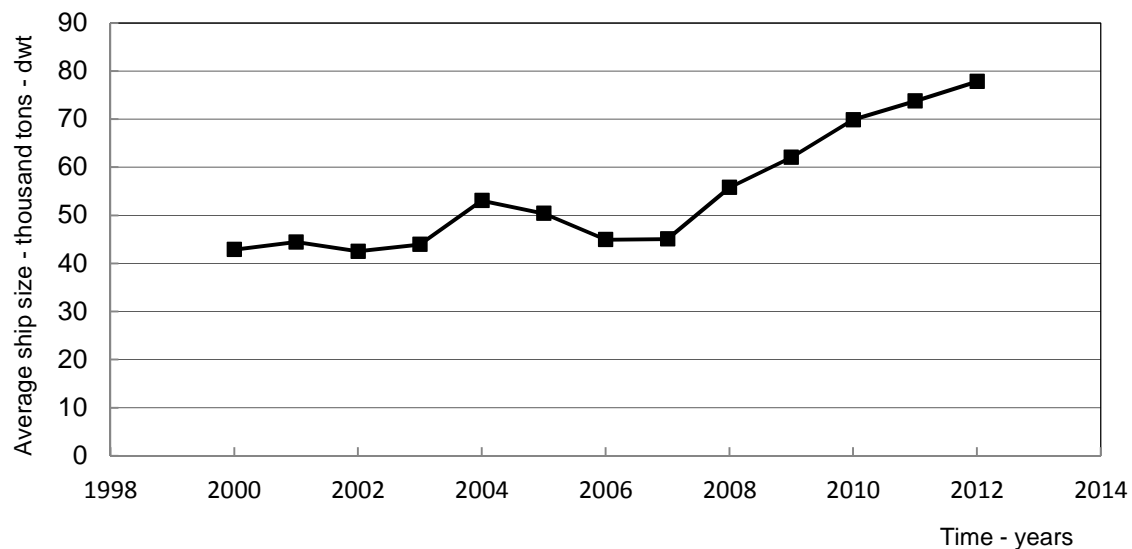


Figure 2 Development of the world's maritime container ship fleet - tonnage on order (period 2000-2013) (dwt – dead weight ton(s) (UNCTAD, 2013)

On the one hand, the larger freight transport vehicles with the greater payload capacity usually perform the smaller number of services and corresponding vehicle-kilometres while transporting given quantities of goods/freight shipments under given conditions. On the other, these vehicles usually have higher empty weight, energy (fuel) consumption, total cost per service in addition to constraints in accessing particular transport (usually loading/unloading) locations and providing the sufficient goods/freight shipments for profitable services, i.e., load factor. The latest particularly relate to the specific category of these vehicles, called “mega” freight transport vehicles considered as the largest in terms of external dimension, gross weight, and payload capacity, all compared to their closest (smaller) counterpart(s). They are easily recognizable within each transport mode: road – mega trucks, rail/intermodal - long freight trains, air - large cargo aircraft, and sea –large container ships.

This paper presents performances of the supply chain(s) served by different including the mega freight transport vehicles. In addition to this introduction, the paper consists of four other sections. Section 2 explains the concept of performances of supply chain(s). Section 3 develops the generic analytical models for estimating performances of the supply chain(s) operating according to the specified scenario(s) under given conditions. Section 4 presents application of the proposed models to the intercontinental supply chain served by the different including the mega container ships. The last section summarises some conclusions.

2 THE CONCEPT OF PERFORMANCES OF SUPPLY CHAIN(S)

2.1 Definition and categorization

The performances of supply chain(s) are considered as their inherent ability to deliver goods/freight shipments from the ultimate suppliers/senders to the ultimate

customers/receivers under given conditions as it is prescribed (planned), i.e., generally efficiently, effectively, and safely. Consequently, as at the similar systems, the performances of supply chains can be classified as infrastructural, technical/technological, operational, economic, environmental, and social (Janic, 2014). Independently on the type of supply chain(s) and characteristics of freight transport vehicles serving them, these performances are inherently interrelated and interacting with each other as shown in Figure 3.

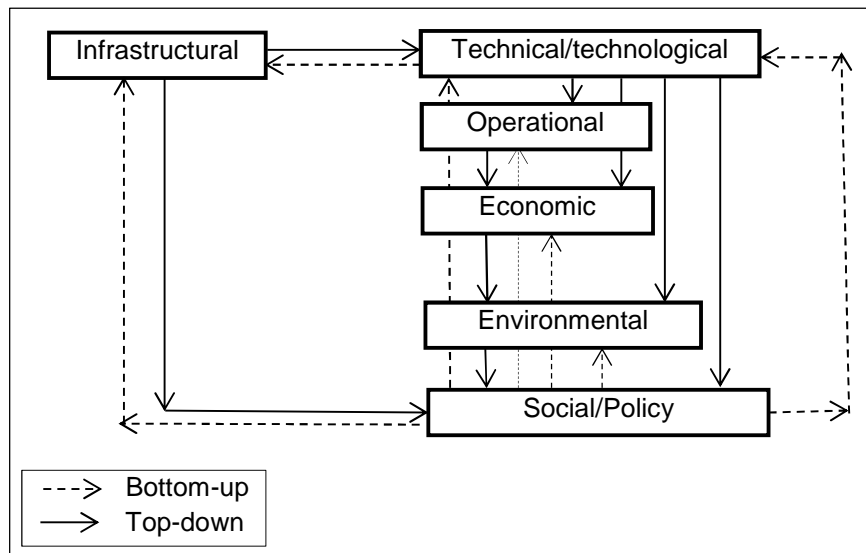


Figure 3 Possible interrelations and interactions of performances of supply chain(s) (Janic, 2014)

As can be seen, in the “top-down” consideration, the infrastructural performances can generally influence the technical/technological performances, and consequently create the mutual influence between these and all other performances. In the “bottom-up” consideration, the social and environmental performances can influence the infrastructural and technical/technological performances and consequently also create the mutual influence of these and all other performances

2.2 Characterization

The performances of supply chains are generally characterized as follows;

Infrastructural performances relate to the physical/spatial characteristics of the chain’s producing, storing, and consuming plants of goods/freight shipments, and the infrastructure of different transport modes (road, rail, inland waterways air, sea and intermodal) connecting them.

Technical/technological performances reflect the capacity of production, storage, and consumption plants including those of the supportive facilities and equipment for loading/unloading, handling, and storing goods/freight shipments before and after their transportation throughout the chain(s). The latest are installed at and around the corresponding plants. The additional performances relate to the dimension (length, width, height, overall configuration), weight (gross, tare, payload), number, size, and location of the

loading/unloading door(s), engines (power, energy/fuel), and the technical speed of freight transport vehicles serving the chain(s).

Operational performances relate to the chain's production/consumption cycle. These are considered to be: the number or quantity of goods/freight shipments to be transported within the chain under given conditions, the frequency of orders of goods/freight shipments and related transport services, the required vehicle fleet, i.e., type and number of vehicles deployed to serve the chain(s) under given conditions, and the (technical) productivity of transport services.

Economic performances can generally be the total and average cost generally including the chain's inventory, handling, and transportation cost of the goods/freight shipments.

Environmental performances are considered to be the energy (fuel) consumption and related direct and indirect emissions of GHG (Green House Gases) and the area of land/space used/taken by the chain(s).

Social performances relate to noise, congestion, and safety of the chain(s). Excessive noise generated by producing, storing, transporting, and consuming goods/freight shipments at and in between the chain(s) hub supplier(s) and the hub customer(s), respectively can burden neighbouring population. Congestion mainly happens during transportation of goods/freight shipments, most frequently nearby the hub supplier(s), the (hub) customers, and along the route(s) between them. Safety reflects the risk of incidents/accidents in the chain(s) that can cause damage and/or loss of properties and/or goods/freight shipments, and the people's injuries and/or loss of lives.

3 THE MODELS OF PERFORMANCES OF SUPPLY CHAIN(S)

3.1 Some previous research

The previous research on dealing with particular performances of the supply chains directly or indirectly has been substantive. The research closely related to that presented in this paper can be classified into three categories addressing: i) general performances of supply chain(s); ii) the role and influence of transport operations on the entire performances of supply chain(s); and iii) the sustainability (greening) of supply chain(s).

The research on the general performances of supply chain(s) has mainly focused on understanding the relationship between the supply chain management (SCM) practice and the supply chain performances (SCP). In such context the performances and their measures have been based on the strategic, operational, and tactical level (Gunasegaran et al., 2004), reliability, responsiveness, cost and assets (Huang et al., 2005; Lat et al., 2002), the overall chains' goals (Otto and Kotzab, 2003), instruments for measuring collaboration between the chain's suppliers and retailers (Simatupang and Shridharan, 2005), performances of the suppliers (Giannakis, 2007), and integration of the performance management process for delivering services into the customer/supplier dyads (Forslund and Jonsson, 2007). In addition, this research has included measuring performances of the supply chain(s) under uncertainty by applying fuzzy logic (Olugu and Wong, 2009), and setting up the criteria for development of the supply chain's performance measurement systems (PMS) including identification of barriers to their implementation (Fauske et al., 2006).

The research on the role and influence of transport operations on the performances of supply chain(s) has mainly addressed understanding the relationships between the transport and logistics operations and possible improvements through the goods/freight shipment(s) delivery speed, quality of service, operating costs, use of facilities and equipment, and savings

energy (Tseng et al., 2005), modelling performances of different spatial and operational configurations of the goods/freight collection/distribution networks (Janic 2005; 2014), and understanding the potential interactions between location of European manufacturing industry, related services, and logistics and freight transport (EC, 1999).

The research on the sustainability (i.e., greening) of supply chain(s) has mainly focused on defining the management of green supply chain(s) means by integrating the environment thinking into the supply chain management including the product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers, and the end-of-life management of the product after its use (Janic et al., 1999; Srivastara, 2007; Stevels, 2002). In addition, this research has related to investigating the possible initiatives, driving forces/actions, and barriers to implementation of the “greening” initiatives by transport and logistics companies in order to reduce the environmental impacts of transport and logistics activities carried out within the given supply chain(s). These all could lead to achievement of the sustainable (green) logistics and supply chain management (Evangelista et al., 2010; WEF, 2009).

In addition, the research on investigating effects/impacts of the mega freight vehicles on the performances of supply chains has not been explicitly carried out. Nevertheless, the infrastructural, technical/technological, operational, economic, environmental, and social performances of these vehicles such as the long intermodal freight trains, road mega trucks, large freight/cargo aircraft, and large container ships have been elaborated on the case-by-case, i.e., vehicle-by-vehicle, basis (Janic, 2014). Consequently, as far as the author’s knowledge, an explicit dealing with performances of supply chains served by the freight transport vehicles of different size/payload capacity including the mega ones is still lacking. This paper intends to partially fill in this gap.

3.2 Objectives and assumptions

The objectives of paper are to develop the analytical models of performances of the given supply chain(s) served by different including the mega freight transport vehicles. Consequently, these models should primarily enable sensitivity analysis of the chain’s performances in dependence on the characteristics of different categories of vehicles serving it. In the present context, the given supply chain has generic (spatial) configuration. This implies that it consists of a single hub supplier, a single hub customer, and the transport infrastructure connecting them. The goods/freight shipments consolidated into TEUs are transported between two hubs by different including the mega freight transport vehicles. The spoke suppliers connect to their hub supplier by the smaller vehicles delivering the smaller shipments of TEUs. The hub customer connects to the spoke customers by the smaller vehicles delivering the smaller shipments of TEUs. Therefore, the models of performances of the above-mentioned (generic) supply chain(s) are based on the following assumptions (Daganzo, 2005; Hall, 1993; Janic et al. 1999; Janic, 2005):

- The hub supplier of a given supply chain(s) is ultimately the production location, i.e., origin, of the goods/freight shipments; the hub customer is ultimately their consumption location, i.e., destination;
- The chain(s)’s production/consumption cycle taking place during the specified period of time satisfies the series of successive orders of goods/freight shipments to be transported between the hub supplier and the hub customer exclusively by the different vehicle fleets including that of mega ones; this implies that, independently of the size of vehicles in the

fleet, there is always sufficient demand justifying the operational (service frequency) and economical (load factor) feasibility of their use;

- The size of a goods/freight shipment(s) is always less than or at most equal to the payload capacity of a vehicle serving the given chain(s);
- The fleet(s) serving given supply chain(s) consists of vehicles of the same size/payload capacity operating with the same load factor.
- The infrastructural and technical/technological performances of the above-mentioned supply chain(s) are assumed to be given as inputs for the models, thus implying considering only the chain's operational, economic, environmental, and social performances; and
- Exclusive use of given fleet of vehicles to serve the supply chain implies the “all-or-nothing principle” of serving demand under given conditions.

3.3 Basic structure of the models

3.3.1 Generic configuration of a supply chain(s)

The generic configuration of a supply chain(s) served by any kind of freight transport vehicles is represented as the H-S (Hub-and-Spoke) transport network whose main nodes are the hub supplier and the hub customer connected by the transport link(s) between them as shown on Figure 4 (a, b). The spokes ‘feeding’ the hub supplier and those ‘fed’ by the hub customer are also shown. As can be seen, the inventories of goods/freight shipments take place at the hub supplier, the hub customer, and along the route between them. Figure 4a shows case a) of exclusive and Figure 4b case b) of simultaneous collecting and loading of goods/freight shipments at the hub supplier, and their exclusive unloading and distributing at the hub customer, respectively. ‘Exclusivity’ implies that the entire shipment is collected before starting its loading, and the entire shipment is unloaded before starting its distribution. ‘Simultaneously’ implies that both collecting and loading of goods/freight shipment(s) on the one end and its unloading and distribution on the other end of the chain can be partially or fully carried out at the same time. In such way, it is possible to manage the inventories of goods/freight shipments and related costs.

3.3.2 Operational performances

The operational performances of the above-mentioned supply chain are considered to be: i) transport service frequency to exclusively: a) serve given demand, and b) enable specified services during the chain's production/consumption cycle; ii) the size of deployed vehicle fleet; and iii) (technical) productivity.

i) Transport service frequency (dep/TU):

a) Serve given demand:

$$f_{ij}(\tau) = \frac{Q_{ij}(\tau)}{\lambda_{ij}q_{ij}} \quad (1a1)$$

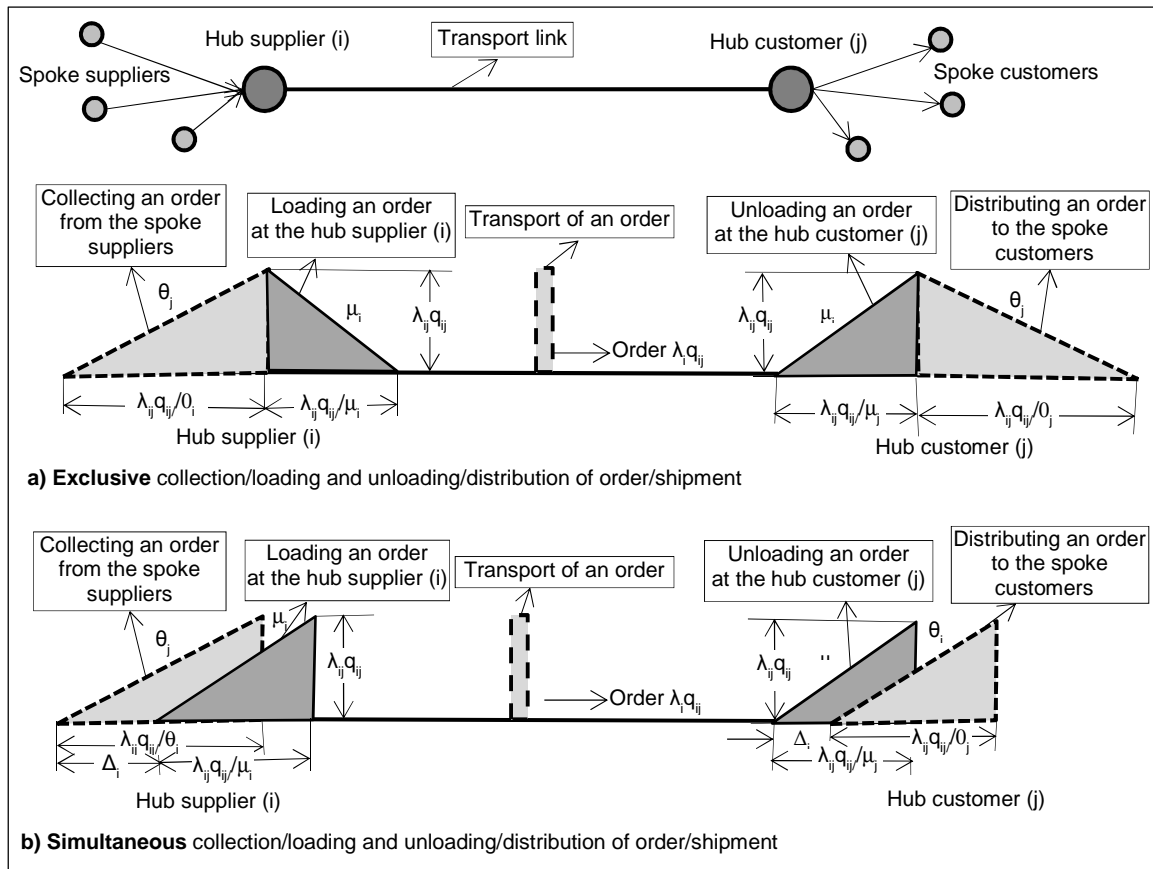


Figure 4 Simplified scheme of the generic configuration of supply chain(s) (Janic, 2014)

a) Enable specified services during the cycle's time:

$$f_{ij}^*(\tau) = \tau / h_{ij}(\tau) \tag{1a2}$$

From Eq. 1a2, the total quantity of goods/freight shipments, which can be transported within the chain during time (τ), is determined as:

$$Q_{ij}^\#(\tau) = \beta_{ij}(\tau) * [\min(f_{ij}(\tau); f_{in}^*(\tau))] * (\lambda_{ij}q_{ij}) \tag{1a3}$$

ii) *The size of deployed vehicle fleet (vehicles/cycle)*

$$N_{ij}(\tau) = \beta_{ij}(\tau) * [\min(f_{ij}(\tau); f_{in}^*(\tau))] * t_{ij}(d_{ij}) \tag{1b}$$

If each vehicle operates within the chain relatively full in both directions, its average turnaround time $t_{ij}(d_{ij})$ in Eq. 1b is estimated as follows:

$$t_{ij}(d_{ij}) = \tau_{ij} + \tau_{ji} = \Delta_{i1} + \frac{\lambda_{ij}q_{ij}}{p_{i1}\mu_{i1}} + \frac{d_{ij}}{s_{ij} * v_{ij}(d_{ij})} + D_{ij} + \Delta_{j1} + \frac{\lambda_{ij}q_{ij}}{p_{j1}\mu_{j1}} + \Delta_{j2} + \frac{\lambda_{ji}q_{ji}}{p_{j2}\mu_{j2}} + \frac{d_{ji}}{s_{ji} * v_{ji}(d_{ji})} + D_{ji} + \Delta_{i2} + \frac{\lambda_{ji}q_{ji}}{p_{i2}\mu_{i2}} \quad (1c)$$

iii) (Technical) productivity (TEU, m³ or ton-km/TU)

$$TP_{ij}(\tau) = Q_{ij}^*(\tau) * s_{ij} * v_{ij}(d_{ij}) \quad (1d)$$

where

TU	is time unit (h, day).
τ	is duration of the chain's production/consumption cycle (TU);
$Q_{ij}(\tau)$	is the quantity of goods/freight shipments to be transported from the hub supplier (i) to the hub customer (j) during the chain's production/consumption cycle (τ) (tons, m ³ , or TEUs/TU);
λ_{ij}, q_{ij}	is the average load factor and the payload capacity, respectively, of a vehicles serving the chain (ij) (tons, m ³ , or TEUs per vehicle);
$h_{ij}(\tau)$	is the average time between the scheduled vehicle departures between the hub supplier (i) and the hub customer (j) during time (τ) (TU);
$\beta_{ij}(\tau)$	is the proportion of realized transport services during the chain's production/consumption cycle of duration (τ);
τ_{ij}, τ_{ji}	is the average time, which a vehicle spends operating in the direction (ij) and (ji), respectively (TU/veh);
Δ_{i1}, Δ_{j1}	is the time between starting vehicle's loading at the hub supplier (i) and unloading at the hub customer (j), respectively (TU);
Δ_{j2}, Δ_{i2}	is the time between starting vehicle's loading at the hub customer (j) and unloading at the hub supplier (i), respectively (TU);
d_{ij}, d_{ji}	is the length of chain's route, i.e., distance between the hub supplier (i) and the hub customer (j), and vice versa, measured along the transport infrastructure link connecting them, respectively (km);
$v_{ij}(d_{ij}), v_{ji}(d_{ji})$	is the vehicle's average (planned) operating speed on the distances (d_{ij}) and (d_{ji}), respectively (km/TU or kts (knots); 1 kts = 1nm/h; nm – nautical mile = 1.852km));
D_{ij}, D_{ji}	is the average delay per transport service due to the traffic conditions on the route connecting the hub supplier (i) and the hub customer (j), and returning back, respectively (TU);
μ_{i1}, μ_{j1}	is the loading and unloading rate of a vehicle at the hub supplier (i) and the hub customer (j), respectively (tons, m ³ or TEU/TU);
p_{i1}, p_{j1}	is the proportion of vehicle's loading and unloading rate used at the hub supplier (i) and the hub customer (j), respectively ($p_{i1}, p_{j1} \leq 1.0$); and
μ_{j2}, μ_{i2}	is the loading and unloading rate of a vehicle at the hub customer (j) and the hub supplier (i), respectively (tons, m ³ or TEU/TU);
p_{j2}, p_{i2}	is the proportion of vehicle loading and unloading rate used at the hub customer (j) and the hub supplier (i), respectively ($p_{j2}, p_{i2} \leq 1.0$); and
s_{ij}, s_{ji}	is the portion of maintained average vehicle planned operating speed under

some kind of irregular operating conditions along the distance (d_{ij}) and (d_{ji}), respectively, caused by disruptive event(s) ($s_{ij} \leq 1.0$)

Eq. 1a1 indicates that the transport service frequency is adjusted to serve demand of goods/freight shipments generated during the chain's production/consumption cycle. Eq. 1a2 implies that the demand of goods/freight shipments is always available and uniformly distributed over the specified period of time and thus the transport service frequency is adjusted to serve it in the regular time intervals. The vehicle's loading and unloading rates μ_{i1} , μ_{j1} , μ_{j2} , and μ_{i2} in Eq. 1c depend of the number of engaged loading/unloading devices (usually cranes) and the loading/unloading rate of each of them. In addition, Eq. 1c indicates that the vehicle turnaround time can be affected during loading at the hub supplier (i), unloading at the hub customer (j), and while operating between them in both directions. If this affection lasts longer, then Eq.1b indicates that the larger fleet may be needed to serve the supply chain(s) under given conditions. As well, Eq.1d indicates that the (technical) productivity of supply chain can also be affected by the affected service frequencies on the one hand, and by the affected speed of realized services on the other.

3.3.3 Economic performances

The economic performances of a given supply chain are considered to be the i) inventory, ii) handling, and iii) transport a) total and b) average cost of a goods/freight shipment(s) served by the chain. If the size of goods/freight shipment corresponds to the vehicle payload capacity, these costs are determined as follows:

i) Inventory cost (€ or \$US)

$$C_{ij/INV}(\lambda_{ij}q_{ij}) = IT_i(\lambda_{ij}q_{ij}) * \alpha_i + (\lambda_{ij}q_{ij}) * \frac{d_{ij}}{s_{ij} * v_{ij}(d_{ij})} * \alpha_{ij} + IT_j(\lambda_{ij}q_{ij}) * \alpha_j \quad (2a)$$

The first and third term in Eq. 2a represent the inventory cost of a goods/freight shipment at the hub supplier (i) and at the hub customer (j), respectively. The second term represents the inventory, i.e., the shipment's cost of time while in transportation between the hubs (i) and (j). From Figure 4, the goods/freight shipment inventory time in Eq. 2a at the hubs (i) and (j), respectively, is determined as follows:

$$IT_i(\lambda_{ij}q_{ij}) = \left\{ \begin{array}{l} \frac{1}{2}(\lambda_{ij}q_{ij})^2 \left[\frac{1}{r_i\theta_i} + \frac{1}{p_i\mu_i} \right] \quad \text{if } a) \\ \max \left\{ 0; (\lambda_{ij}q_{ij})^2 \left(\frac{1}{p_i\mu_i} - \frac{1}{2r_i\theta_i} \right) + (\lambda_{ij}q_{ij})\Delta_{i1} \right\} \quad \text{if } b) \end{array} \right\} \quad (2b)$$

and analogously

$$IT_j(\lambda_{ij}q_{ij}) = \left\{ \begin{array}{l} \frac{1}{2}(\lambda_{ij}q_{ij})^2 \left[\frac{1}{r_j\theta_j} + \frac{1}{p_j\mu_j} \right] \text{ if } a) \\ \max \left\{ 0; (\lambda_{ij}q_{ij})^2 \left(\frac{1}{p_j\mu_j} - \frac{1}{2r_j\theta_j} \right) + (\lambda_{ij}q_{ij})\Delta_{j1} \right\} \text{ if } b) \end{array} \right\} \quad (2c)$$

ii)/iii) Handling and transport cost (€ or \$US)

$$C_{ij/H-TRA}(\lambda_{ij}q_{ij}) = c_i * (\lambda_{ij}q_{ij}) + c_{ij}(\lambda_{ij}q_{ij}) * (\lambda_{ij}q_{ij}) * d_{ij} + c_j * (\lambda_{ij}q_{ij}) \quad (2d)$$

a) Total (inventory + handling + transport) cost (€ or \$US)

$$C_{ij}(\lambda_{ij}q_{ij}) = C_{ij/INV}(\lambda_{ij}q_{ij}) + C_{ij/H-TRA}(\lambda_{ij}q_{ij}) \quad (2e)$$

b) Average total cost (€ or \$US/TEU-km or ton-km)

$$\bar{c}_{ij}(\lambda_{ij}q_{ij}) = C_{ij}(\lambda_{ij}q_{ij}) / [(\lambda_{ij}q_{ij}) * d_{ij}] \quad (2f)$$

where

- θ_i, θ_j is the rate of collecting and distributing goods/freight shipments at the hub supplier (i) and the hub customer (j), respectively (tons, m^3 or TEU/TU);
- r_i, r_j is the proportion of rate of collecting and distributing goods/freight shipments used at the hub supplier (i) and the hub customer (j), respectively ($r_i, r_j \leq 1.0$);
- c_i, c_j is the handling (loading/unloading/transshipment) cost of a goods/freight shipment at the hub supplier (i) and the hub customer (j), respectively (€/ton, m^3 , or TEU)); and
- $\alpha_i, \alpha_{ij}, \alpha_j$ is the cost of goods/freight shipment inventory time while at the hub supplier (i), in transportation, and at the hub customer (j), respectively (€/ton or m^3 or TEU)/h or day).

The other symbols are analogous to those in Eq. 1 (a, b, c, d). By replacing the size of shipment ($\lambda_{ij}q_{ij}$) by the quantity of goods/freight generated during chain's production/consumption cycle (Q_{ij}), the corresponding economic performances can be estimated similarly from Eq. 2 (a, b, c, d). In addition, this Eq. indicates that the goods/freight shipment inventory time and related cost could be compromised in any handling phase in the chain, i.e., during collecting, loading, transporting, unloading, and distributing.

3.3.4 Environmental performances

The environmental performances of a given supply chain(s) are considered to be: i) the energy (fuel) consumption and related emissions of GHG (Green House Gases), and ii) land/space used/taken.

i) Energy (fuel) consumption and emissions of GHG (Green House Gases)

The total and average fuel consumption, respectively, from Eq. 1a3, are estimated as follows:

$$FC_{ij}(\tau) = \left\{ \beta_{ij}(\tau) * \left[\min(f_{ij}(\tau); f_{in}^*(\tau)) \right] \right\} * FC[q_{ij}; v_{ij}(d_{ij})] * d_{ij} \quad (\text{litre, kg, ton, or kWh})$$

$$\underline{AFC}_{ij}(\tau) = FC_{ij}(\tau) / [Q_{ij}^*(\tau) * d_{ij}] \quad (\text{litre, kg, ton or kWh/TEU - km})$$

$$\text{or ton - km}$$
(3a)

The total and average emissions of GHG, respectively, are determined based on Eq. 3a as follows:

$$EM_{ij}(\tau) = \sum_{k=1}^K FC_{ij}(\tau) * e_k \quad (\text{kg or ton})$$

$$AEM_{ij}(\tau) = EM_{ij}(\tau) / [Q_{ij}^*(\tau) * d_{ij}] \quad (\text{kg /TEU - km or ton - km})$$
(3b)

where

$FC[q_{ij}; v_{ij}(d_{ij})]$ is the energy (fuel) consumption of a vehicle of the payload capacity (q_{ij}) serving the supply chain (ij) at the speed $v_{ij}(d_{ij})$ on the distance (d_{ij}) (litre. kg, or KWh/km);

e_k is the emission rate of (k)-th GHG from the consumed energy (fuel) of a vehicle serving the supply chain (ij) (kg of GHG/ litre, kg, or KWh); and

K is the number of different GHG emitted from the consumed energy (fuel) by a vehicle serving the supply chain (ij).

The other symbols are analogous to those in the previous Eqs.

ii) Land used/taken

The land used/taken by a given supply chain is expressed as an area of land or space at the supplier and the hub customer intended to park vehicles during their loading and unloading, respectively. If the frequency of vehicles during the production/consumption cycle of the supply chain (ij) is determined from Eq. 1 (a1, a2), then the number of required parking stands for vehicles at the hub supplier (i) and the hub customer (j), respectively, per cycle is estimated as follows:

$$n_i(\tau) = \beta_{ij}(\tau) * \left[\min(f_{ij}(\tau); f_{in}^*(\tau)) \right] * \tau_{i1} = \beta_{ij}(\tau) * \left[\min(f_{ij}(\tau); f_{in}^*(\tau)) \right] * \left(t_{i2} + \Delta_{i1} + \frac{\lambda_{ij} q_{ij}}{p_{i1} \mu_{i1}} \right) \quad (3c1)$$

and

$$n_j(\tau) = \beta_{ij}(\tau) * \left[\min(f_{ij}(\tau); f_{in}^*(\tau)) \right] * \tau_{j1} = \beta_{ij}(\tau) * \left[\min(f_{ij}(\tau); f_{in}^*(\tau)) \right] * \left(\Delta_{j1} + \frac{\lambda_{ij} q_{ij}}{r_{j1} \mu_{j1}} + t_{j2} \right) \quad (3c2)$$

where

τ_{i1}, τ_{j1} is the average occupancy time of a parking stand during handling vehicle(s) at the hub supplier (i) and the hub customer (j), respectively, (TU).

t_{i2}, t_{j2} is the time of unloading vehicle from the previous task at the hub supplier (i) and

loading it for the forthcoming task at the customer (j), respectively (TU)

The other symbols are analogous to those in the previous Eqs.

Eq. 3 (c1, c2) assumes that the same parking stand is used for both loading and unloading of the vehicle(s). Otherwise, the terms t_{i2} and t_{j2} can be neglected. In addition, the terms (A_{i1}) and (A_{j1}) indicate that the vehicle(s) can occupy the parking stand also while waiting for starting loading and unloading operation, respectively. Thus, the number of required parking stands for loading and unloading vehicles mainly depends, in addition to the service frequency and size of freight/goods shipment, also on the actual loading and unloading rate(s), i.e., the corresponding times. From Eq. 3 (c1, c2), the net area of land or space taken for parking vehicles at the hub supplier (i) and the hub customer (j), respectively, not including the manoeuvring space, is determined as follows:

$$A_i(\tau) = n_i(\tau) * (L_{ij} * w_{ij}) \quad \text{and} \quad A_j(\tau) = n_j(\tau) * (L_{ij} * w_{ij}) \quad (3d)$$

where

L_{ij}, w_{ij} is the length and width of the vehicle's footprint relevant for dimensioning parking stand (m, m).

3.3.5 Social performances

The social performances of a given supply chain are considered to be i) noise; ii) congestion; and iii) safety (i.e., the risk of potential traffic incidents/accidents), these all primarily related to the chain's transport operations (Janic and Vleugel, 2012).

i) Noise

Noise is generally generated by transport vehicles (trains, trucks, barges, and aircraft) serving the supply chain while passing-by an exposed observer. The sea ships are excluded from consideration mainly due to the nature of their operations on the open sea.

The noise mainly depends on its level generated by the source, i.e., moving vehicle, and its distance from an exposed observer. This distance changes over time, during the vehicle's passing-by, as follows:

$$\rho_{ij}^2(t) = (L_{ij} / 2 + \beta_{ij} - v_{ij}t)^2 + \gamma_{ij}^2 \quad \text{for } 0 < t \leq (L_{ij} + 2\beta_{ij} / v_{ij}) \quad (3e)$$

The noise to which the above-mentioned observer is exposed during the passing-by vehicle is determined as follows:

$$L_{eq}[\rho_{ij}(t), v_{ij}] = L_{eq}(\gamma_{ij}, v_{ij}) - 8.6562 \ln[\rho_{ij}(t) / \gamma_{ij}] \quad (3f)$$

The noise from $f_{ij}(\tau)$ successive passing-by vehicles during the period (τ), i.e., per chain's production/consumption cycle, is determined as follows:

$$L_{eq}[f_{ij}(\tau)] = 10 \log \sum_{r=1}^{f_{ij}(\tau)} 10^{\frac{L_{eq}(\rho_{ij}(t), v_{ij})}{10}} \quad (3g)$$

where

$L_{eq}(\gamma_{ij}, v_{ij})$ is the noise by a passing-by vehicle at the speed (v_{ij}) and distance (γ_{ij}) (decibels - dBA);
 v_{ij} is the speed of a passing-by vehicle serving the supply chain (ij) (km/h); and
 γ_{ij}, β_{ij} is the shortest (right angle) and slant distance, respectively, between the noise source, i.e., moving vehicle serving the supply chain (ij), and an exposed observer (m).

The other symbols are analogous to those in the previous Eqs.

The second term in Eq. 3f represents the noise attenuation over an area free of barriers between the noise source, i.e., moving vehicles serving the given supply chain, and an exposed observer.

ii) Congestion

Congestion depends on the type of vehicle/transport mode serving the given supply chain (ij). In general, the freight trains, aircraft, and sea ships are given the time slots for accessing and using the transport infrastructure around and between the hub supplier(s) and the hub customer(s) (rail/intermodal terminals, airports, sea port terminals) thus diminishing substantively their contribution to the overall congestion.

For example, trucks serving the supply chain (ij) cause congestion and consequent time losses of individual vehicles/cars tailing behind due not to be able to overtake them along the road(s) connecting the hub supplier (i) and the hub customer (j). The time a vehicle/car spends before overtaking a truck serving the supply chain (ij) can be estimated using the theory of stochastic and deterministic queuing systems. This assumes that the vehicles/cars are waiting for entering the road segment currently occupied by a truck in which case they represent the arriving customers. The time the truck occupies the road segment represents their service time. Consequently, the average time a vehicle/car is waiting before starting to overtake the given truck is estimated as follows (Van Woenseland Vandaele, 2007):

$$W_{q/ij/c} = \begin{bmatrix} L_{ij/t} / (v_{ij/t} - L_{ij/t} * \Lambda_{ij/c}) & \text{if } \Lambda_{ij/c} < v_{ij/t} / L_{ij/t} \\ (1/2) \Delta t_{ij} (L_{ij/t} \Lambda_{ij/c} / v_{ij/t} - 1) & \text{if } \Lambda_{ij/c} > v_{ij/t} / L_{ij/t} \end{bmatrix} \quad (3h)$$

where

$L_{ij/t}$ is the length of a truck serving the supply chain (ij) including the safe front and back buffer distance (space) from the other vehicles (m);
 $v_{ij/t}$ is the average speed of a truck serving the supply chain (ij) (m/s);
 $\Lambda_{ij/c}$ is the intensity of flow of vehicles/cars intending to overtake, i.e., to “occupy the space” currently occupied by the truck serving the supply chain (ij) (veh/s); and
 Δt_{ij} is the time in which the intensity of flow of vehicles/cars to overtake the truck serving the supply chain (ij) is greater than the truck service time (s).

The total waiting time of vehicles tailing behind all trucks serving the given supply chain can be calculated by multiplying the transport service frequency during the chain’s production/consumption cycle and the average waiting time determined by Eq.3h.

iii) Safety (i.e., the cost of risk of loss of a vehicle in an accident)

The cost of risk of loss of a vehicle (including its load) in an accident per given chain’s production/consumption cycle is estimated as follows;

$$C_{RAC}(q_{ij}) = a_{ij} * IP(q_{ij}) \quad (3i)$$

where

a_{ij} is the probability of an accident causing a loss of a vehicle and its load while serving the supply chain (ij) (probability of event/TU); and

$IP(q_{ij})$ is the insurance premium for a vehicle of the payload capacity (q_{ij}) serving the supply chain (ij).

The other symbols are analogous to those in the previous Eqs.

4 APPLICATION OF THE MODELS OF PERFORMANCES OF THE SUPPLY CHAIN(S)

4.1 The case

The above mentioned models of performances of supply chain(s) are applied to the case of supply chain between North Europe and Far East Asia served by the liner container shipping. The hub supplier is assumed to be the port of Rotterdam – APM Terminals Rotterdam (The Netherlands) and the hub customer is assumed to be the port of Shanghai – Yangshan Deepwater Port Phases 1/2 or 3/4 (People Republic of China). Currently, this is one of the world's busiest chains (sea trading routes)¹ shown in Figure 5.

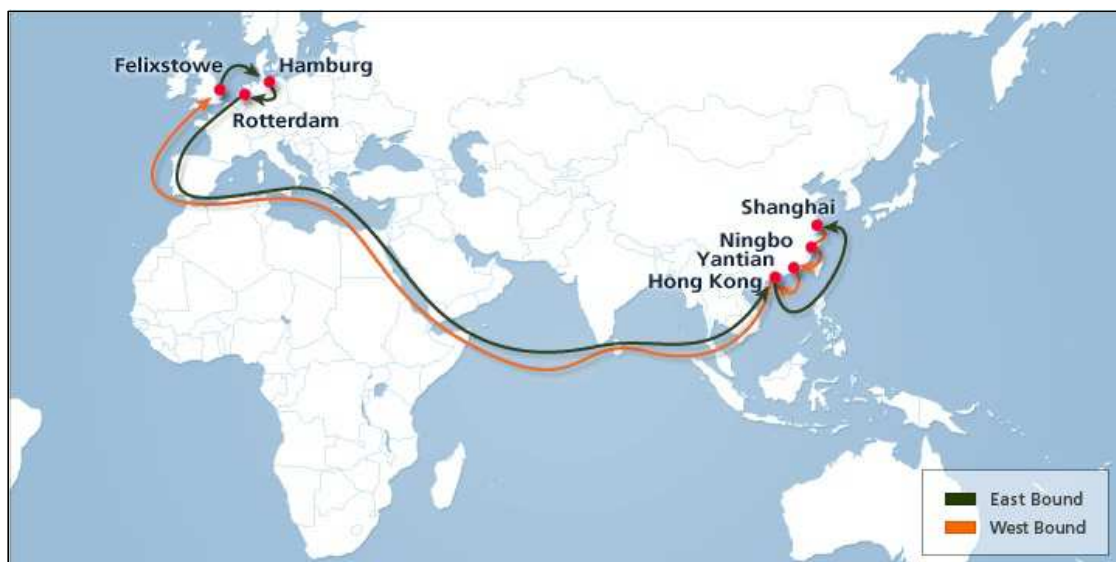


Figure 5 Simplified scheme of geography of the given supply chain – the liner shipping route Rotterdam – Shanghai (<http://www.ship.gr/news6/hanjin28.htm>)

¹ This chain (sea trading route) included in the WCI (World Container Index) together with other 10 most voluminous world's container chains (sea trading routes) shares about 35% of their total volumes (TEUs) (<http://www.worldcontainerindex.com/>).

The container terminals at both ports enable access and operation of the large container ships including the currently largest Triple E Maersk. The collection and distribution of goods/freight shipments (TEUs) at both ports is carried out by rail/intermodal, road, inland waterway (barge), and feeder (including short-sea) vessel transport modes (Zhang et al, 2009). Two scenarios of operating the given chain (route) are considered: the first implies exclusive use of container ships of the capacity of 4000 TEU (or the current Panamax); the other implies exclusive use of container ships of the capacity of 18000 TEU (i.e., Neo Panamax represented by Triple E class ship started operations by Maersk in the year 2013) (AECOM/URS, 2012: <http://www.worldslargestship.com/>). The length and width (beam) of the container ships, similarly as their above-mentioned capacity, are given by design (http://en.wikipedia.org/wiki/List_of_largest_container_ships). Scheme of scale of both ships is shown on Figure 6.

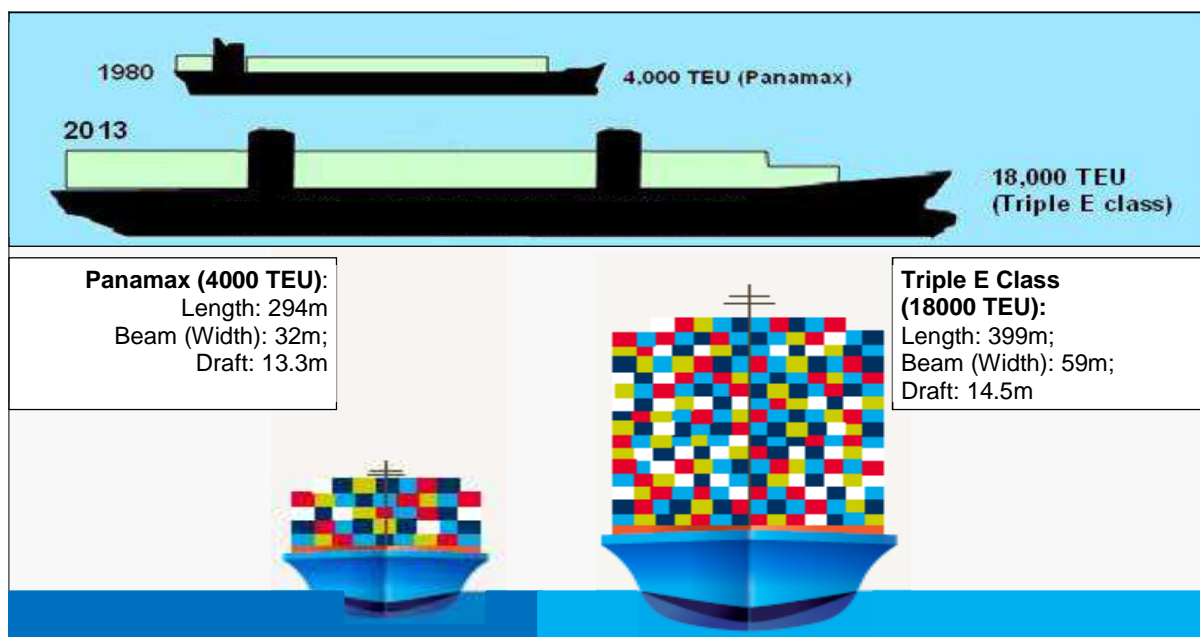


Figure 6 Scheme of scale of container ships used in the given supply chain (PR, 2011; http://en.wikipedia.org/wiki/Container_ship)

In addition, only direct transportation of the containerized goods/freight shipments in the single direction of the chain is considered. Due to the specificity of given case, the social performances such as noise and congestion, as defined in the above-mentioned models, are not considered. However, this does not compromise the quality and generosity of the models' application. In both scenarios, the ships performing transport services are assumed to operate at the typical slow steaming speed of 20 kts (knots) and super slow steaming speed of 15 kts (1kt = 1nm/h; nm – nautical mile) (SCG, (2013).

4.2 Input data

The input data for application of the proposed models to the given supply chain are collected from the case itself and the other different sources and given in Table 1.

Table 1 Input data for application of the models of performances to the given supply chain – liner shipping route Rotterdam (The Netherlands) – Shanghai (China)

Input variable	Notation/Unit	Value
• Duration of the chain's production/consumption cycle	τ (year(s))	<u>1</u>
• Number of containers per chain's production/consumption cycle	Q_{ij} (TEU/year)	<u>748800</u>
• Container ship capacity	q_{ij} (TEU/ship)	<u>4000; 18000</u>
• Container ship length	L_{ij}/q_{ij} (TEU/ship)	<u>294</u> (4000); <u>399</u> (18000)
• Container ship beam (width)	w_{ij}/q_{ij} (TEU/ship)	<u>32</u> (4000); <u>59</u> (18000)
• Container ship load factor	λ_{ij}	<u>0.80</u> (4000); <u>0.80</u> (18000)
• Time between the ships' scheduled departures between hubs (days)	h_{ij}/q_{ij} (TEU/ship)	<u>1.5</u> (4000) <u>7</u> (18000)
• Collection rate of containers at the hub supplier port	θ_i (TEU/day)	<u>1100</u>
• Proportion of used collection rate of containers at the hub supplier port	r_i	<u>1.0</u>
• Distribution rate of containers at the hub customer port	θ_i (TEU/day)	<u>1100</u>
• Proportion of used distribution rate of containers at the hub customer port	r_i	<u>1.0</u>
• Loading rate of containers at the hub supplier port	μ_i (TEU/h)	<u>92</u> (3-4 cranes)/ <u>215</u> (7-8 cranes)
• Proportion of used loading rate of containers at the hub supplier port	p_{i1}	<u>1.0</u>
• Unloading rate of containers at the hub customer port	μ_i (TEU/h)	<u>94</u> (3-4 cranes)/ <u>215</u> (7-8 cranes)
• Proportion of used unloading rate of containers at the hub customer port	p_i	<u>1.0</u>
• Time between starting collecting and loading containers at the hub supplier port	Δ_i (day(s))	<u>1</u>
• Time between starting unloading and distributing containers at the hub consumer port	Δ_i (day(s))	<u>1</u>
• Operating distance between the hub ports	d_{ij} (nm)	<u>10525</u>
• Average operating speed of container ship	v_{ij} (kts)	<u>20</u> (Slow steaming) <u>15</u> (Super slow steaming)
• Portion of the maintained average ship's operating speed	s_{ij}	<u>1.0</u>
• Proportion of realized transport services	β_{ij}	<u>1.0</u>
• Average delay per realized transport service	D_{ij} (days)	<u>0.0</u>
•		
• Container inventory cost at the hub ports	α_i, α_j (€/TEU-day)	<u>124; 124</u>

• Container cost of time in transportation	α_{ij} (€/TEU-day)	<u>10.6</u>
• Container handling cost at the hub supplier port	c_i (€/TEU)	<u>185</u>
• Container handling cost at the hub customer port	c_j (€/TEU)	<u>58</u>
• Container ship operating cost	c_{ij} (€cents/TEU-nm)/ v_{ij} (kts)/ q_{ij} (TEU/ship)	<u>9.90/20; 5.49/15 (4000)</u> <u>2.01/20; 1.13/15 (18000)</u>
• Average fuel consumption of container ship	$f_{c/ij}$ (ton/day)/ v_{ij} (kts)/ q_{ij} (TEU/ship)	<u>221/20; 111/15 (4000)</u> <u>249/20; 150/15 (18000)</u>
• Average emission rate of GHG (Green House Gases) of container ship	e_{ij} (tonCO _{2e} /day)/ v_{ij} (kts)/ q_{ij} (TEU/ship)	<u>688/20; 346/15 (4000)</u> <u>775/20; 467/15 (18000)</u>
• Average occupancy time of a berth by a ship at the hub supplier port	τ_{ij} (days)/ μ_i (TEU/h)/ q_{ij} (TEU/ship)	<u>1.45/ 92/(4000)</u> <u>6.52/92/(18000)</u> <u>2.79/215/(18000)</u>
• Average occupancy time of a berth by a ship at the hub customer port	τ_{ij} (days)/ μ_i (TEU/h)/ q_{ij} (TEU/ship)	<u>1.41/ 94/(4000)</u> <u>6.38/94/(18000)</u> <u>2.79/215/(18000)</u>
• Risk of accident of container ship	a_{ij} (probability of 1 event/year)	<u>8.876 * 10⁻⁴</u>

The number of containers (TEU) per chains' production/consumption cycle of duration of one year is determined by assuming the service frequency by the Triple E class ships of 1dep/week, the Panamax class ships of 5depts/week, and the average load factor of both ship classes of 0.80. These give the total annual number of 748800 TEUs to be transported within the chain according the specified scenarios implying using exclusively one class of ships under given conditions. This is, however, only about one sixth of the total annual number of TEUs transported within the chain

(<http://www.worldcontainerindex.com/>).

The rates of collection and distribution of goods/freight shipments (TEUs) are set up regarding the service schedule of different inland transport modes serving the ports (terminals) at both ends of the chain (route) (Zhang et al., 2009). The container loading and unloading rates are set up based on the empirical evidence from both ports/terminals. In general, both Panamax and Triple E class ships are loaded/unloaded by using 3-4 cranes simultaneously (Mongelluzzo, 2013). In addition, it is considered that the Triple E class ships have started to be loaded/unloaded by up to seven to eight cranes simultaneously at both ends of the chain (route) (SCG, 2013). All selected crane rates are considered to be fully operational over the period of 24h/day.

The time between docking and starting loading and unloading ships at the corresponding ports is chosen as an illustration (This could be reasonable regarding the administrative procedures to be carried out after the ship(s) docks at berths).

The ships are assumed to operate along the route at the constant (slow or super slow steaming) speed(s) without its substantive variations (<http://www.sea-distances.org/>). This implies that all transport services are assumed to be perfectly reliable, i.e., without delays along the route and consequently at the destination. .

The inventory cost of container(s) during collection and loading at the hub supplier port (Rotterdam) and unloading and distribution at the hub customer port (Shanghai) is estimated based on the average retail value of goods in containers and typical share of the inventory cost (25%) in that value (REM Associates, 2014; Rodrigue, 2013). The cost of container time

during transportation is estimated as an average for goods/freight shipments carried out by the sea transport mode (VTI, 2013).

The handling cost of containers at both port terminals is based on the empirical evidence (EC, 2009). The operating cost container ship(s) operating on open sea are estimated respecting the effects of cruising/operating speed(s) on the fuel consumption, fuel price (assumed constant), and the share of fuel cost in the total ship's operating costs (AECOM/URS, 2012; Cullinane and Khanna, 2000; Davidson, 2014; Stopford, 2003; <http://www.scdigest.com/ontarget/13-09-12-1.php?cid=7401>).

The fuel consumption of container ship(s) is estimated as the quantity per day while operating on open sea at the given operating/cruising speed. In addition, the corresponding emissions of CO₂ (Carbon Dioxide) as a predominant one in the total emissions of GHG are calculated using the emission rate of: $e_k = 3.114 \text{ gCO}_2/\text{g}$ of fuel (No. 6 Diesel or HFO (Heavy Fuel Oil)). The fuel consumption and related emissions of CO₂ during the ships' time at berths in the ports are not taken into account (AECOM/URS, 2012; Janic, 2014; Rodrigue, 2013a; <http://www.scdigest.com/ontarget/13-09-12-1.php?cid=7401>).

Finally, the risk of incidents/accidents causing a loss of one container ship(s) per period of time (one year) is estimated as the product of two probabilities: i) of losing a container ship in a freight ship's accident; and ii) of happening such accident within the given chain/route (region). The former probability is estimated as the quotient of the total number of lost container ships (35) and the total number of lost (freight/cargo) ships in accidents (1547). The latter probability is estimated as the quotient of the number of ship lost in the accidents happened along and near the given chain (route) and the total number of ships lost at ten geographical locations worldwide (0.51). Both probabilities are estimated using the relevant data for the period 2001-2013 (Allianz, 2013; UNCTAD, 2013).

4.3 Analysis of results

The results from application of the models of performances to the given case of supply chain based on the input data in Table 1 are shown in Figures 7, 8, 9, and 10.

4.3.1 Infrastructural and technical/technological performances

The infrastructural and technical/technological performances of the given supply chain are specified in the form of inputs for the models of other performances as it is given in Table 1. The former implicitly assume given demand of goods/freight shipments during the chain's production/consumption cycle, availability of the berths in both port terminals to accommodate container ships of any size including the mega ones, and the length of sailing route between the hub ports of the chain. The latter include the container ship characteristics (payload capacity and dimension), and the number and rate of loading/unloading devices (cranes) of container ships, including reliability of their daily operation.

4.3.2 Operational performances

The operational performances of the given supply chain such as service frequency, fleet size, and technical productivity are shown in Figure 7 a, b, c, respectively. .

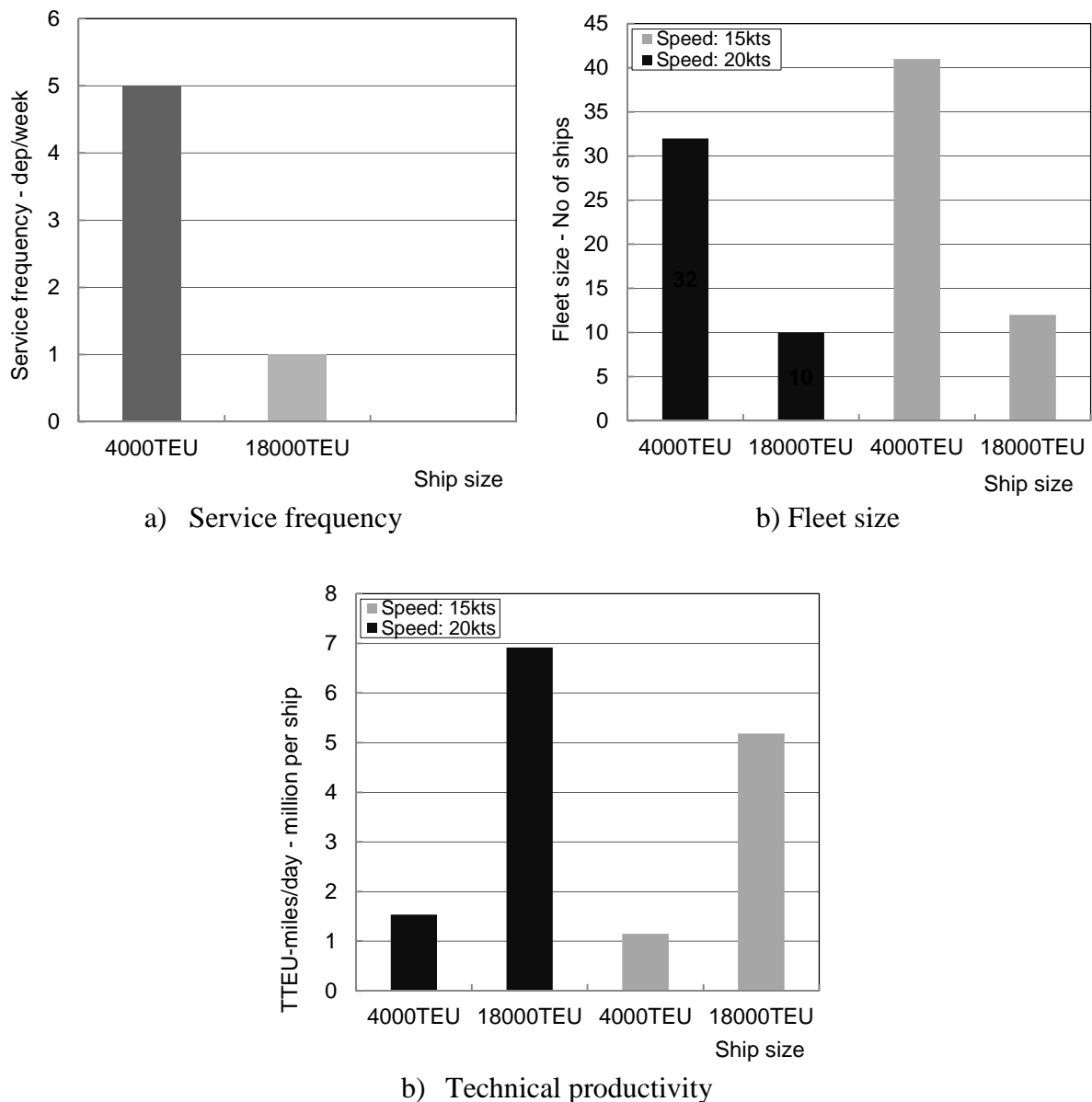
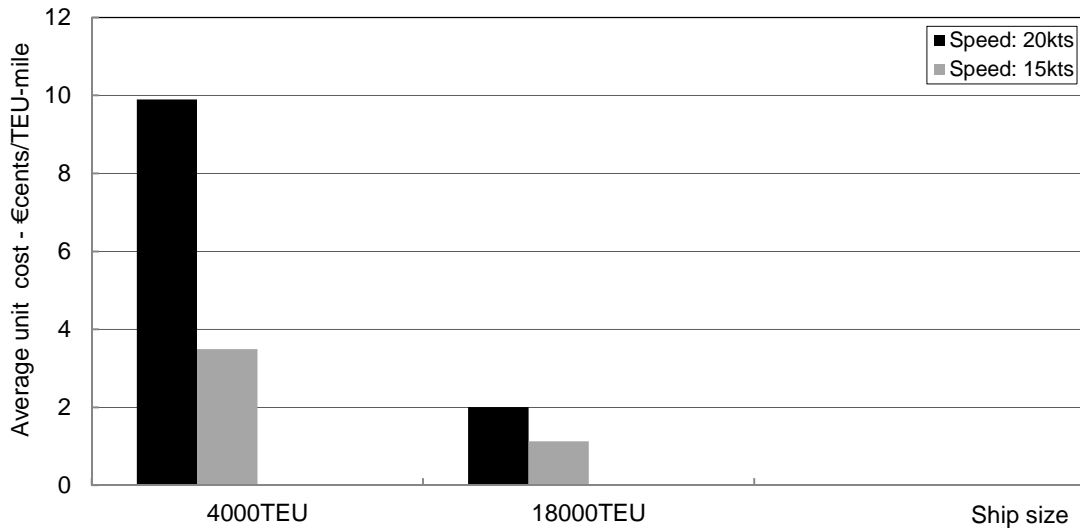


Figure 7 Operational performances of the given supply chain

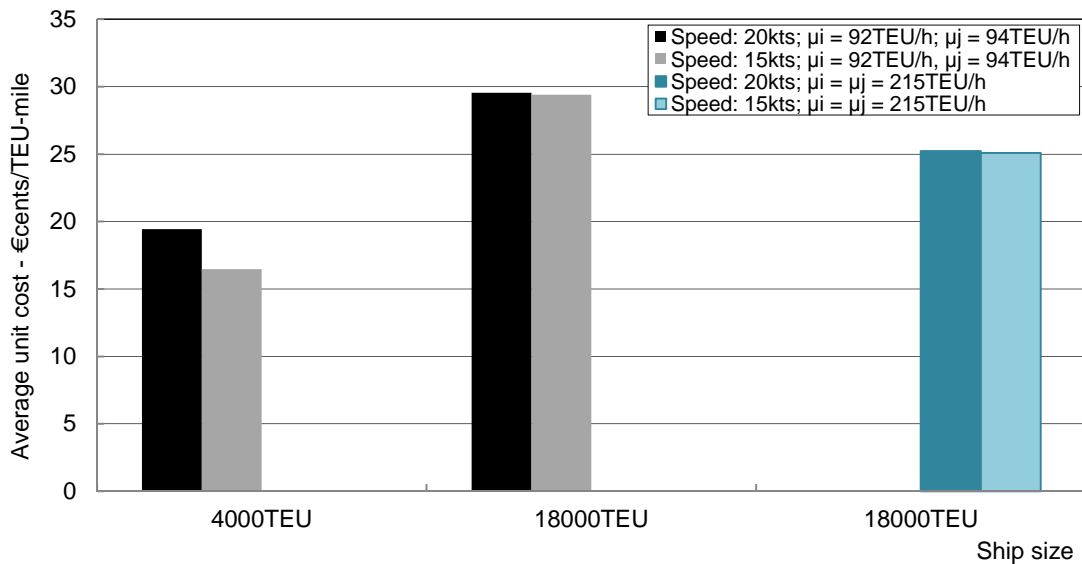
Figure 7a shows that the transport services by the smaller ships need to be more frequent than those by the mega ships, i.e., for about 5 times, in order to transport the required number of containers (TEUs) in the given supply chain under given conditions. Figure 7b shows that such higher service frequency requires for about three times greater fleet of smaller ships than that of the mega ships. Both fleets need to be further increased (for about 35% and 20%, respectively) if operating at the super slow (15kts) instead of the slow (20kts) steaming speed. Figure 7c shows that the technical productivity of mega ships is higher than that of their smaller counterparts in proportion to difference in their size/capacity. However, at both classes of ships this productivity decreases (for about 33%) with reducing of the operating/cruising speed.

4.3.3 Economic performances

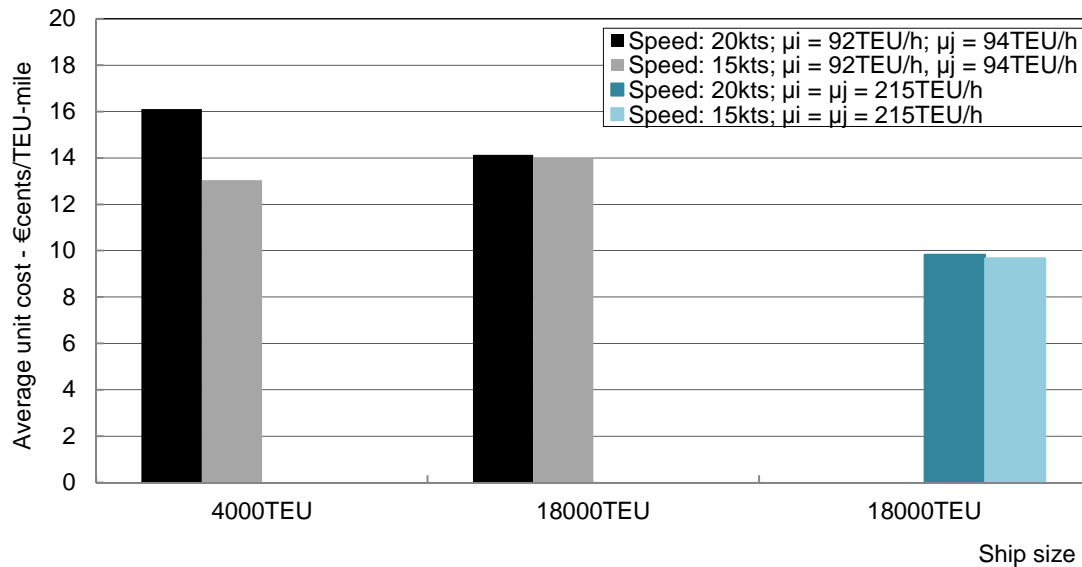
The economic performances of the given supply chain such the average ship (transport) cost, the average cost of supply chain including the inventory cost during collecting/loading and unloading/distributing of containers (TEUs), and the average chain's cost including only the inventory cost during loading and unloading of containers (TEUs) are shown in Figure 8 a, b, and c, respectively.



a) Average transport (ship) operating cost



b) Average chain's cost including the inventory cost during collecting/loading and unloading/distributing containers (TEUs)



c) Average chain's cost including only the inventory cost during loading and unloading containers (TEUs)

Figure 8 Economic performances of the given supply chain

Figure 8a shows that, in the relative terms, if exclusively transport cost are considered, the mega ship(s) is for about 5 times more cost efficient than its smaller counterpart(s), while operating on open sea at either steaming speed (20kts or 15kts). This unit cost difference appears to be in line with differences in the ships' size/capacity, thus confirming existence of the substantive economies of scale of the mega ship(s) under given conditions. Figure 8b shows the total chain's average cost consisting of the inventory and handling cost of collecting/loading and unloading/distributing containers (TEUs) at hub ports, their time cost in transportation, and transport cost. In such case, if the fleet of smaller ships serves the chain, it will be more cost efficient (for about 52% and 79%) than if being served by the fleet of mega ships at either the slow (20kts) and super slow (15kts) steaming speed, respectively. Speeding up of the loading and unloading of the fleet of mega ships at the hub ports decreases this still positive difference for the fleet of smaller ships to about 30% (at slow) and 52% (at super slow) steaming speed. In addition, reducing the steaming speed decreases the chain's average costs much more when served by the fleet of smaller than by the fleet of mega ships, i.e., for about 24% and 1-1.5%, respectively.

Figure 8c shows that the chain's total average cost decrease by excluding the inventory cost during collecting and distributing containers (TEUs) at the hub ports. This time the chain becomes more cost efficient when served by the fleet of mega ships operating at the slow steaming speed (20kts) (for about 14%). However, the chain becomes less cost efficient (for about 8%) if the fleet of mega ships serves it at the super slow steaming speed (15kts). In case of speeding up the loading and unloading of mega ships at the hub ports, the chain's inventory cost substantively decreases causing decreasing of the total average cost. Consequently, if all other cost remain unchanged, the chain served by the fleet of mega ships operating at the slow and super slow steaming speed(s) becomes much more cost efficient (62% and 34%, respectively) than in the case when being served by the fleet of smaller counterparts.

Table 2 gives the structure of the chain's average cost when the inventory cost during collecting/loading and unloading/distribution of containers (TEUs) at the hub ports are included. As can be seen, the share of this (inventory) cost is much lower and the share of transport cost is much higher in the total cost if the chain is served by the fleet of smaller than that of mega ships, independently on their operating speed(s). In any case, reducing the operating speed

Table 2 Structure of the total cost of given supply chain: - The inventory cost during collecting/loading + unloading/distributing containers (TEUs) included

<u>Operating characteristics</u>	<u>Container ship capacity (TEU)</u>		
	<u>4000</u>	<u>18000</u>	<u>18000</u>
Loading/Unloading rate (TEU/h)	92/94	92/94	215/215
Operating speed (kts)	20/15	20/15	20/15
<u>Cost component (%)</u>			
Inventory	38/49	85/88	83/86
Handling	12/14	8/8	9/9
Transport	50/37	7/4	8/5

contributes to increasing of the share of inventory cost on the account of the share of transport cost. Speeding up the loading and unloading of the mega ships at the hub ports reduces very little the share of inventory cost compared to that under common loading and unloading .speed

Table 3 gives the structure of the chain's cost when only the inventory cost during loading and unloading of containers (TEUs) at the hub ports is taken into account.

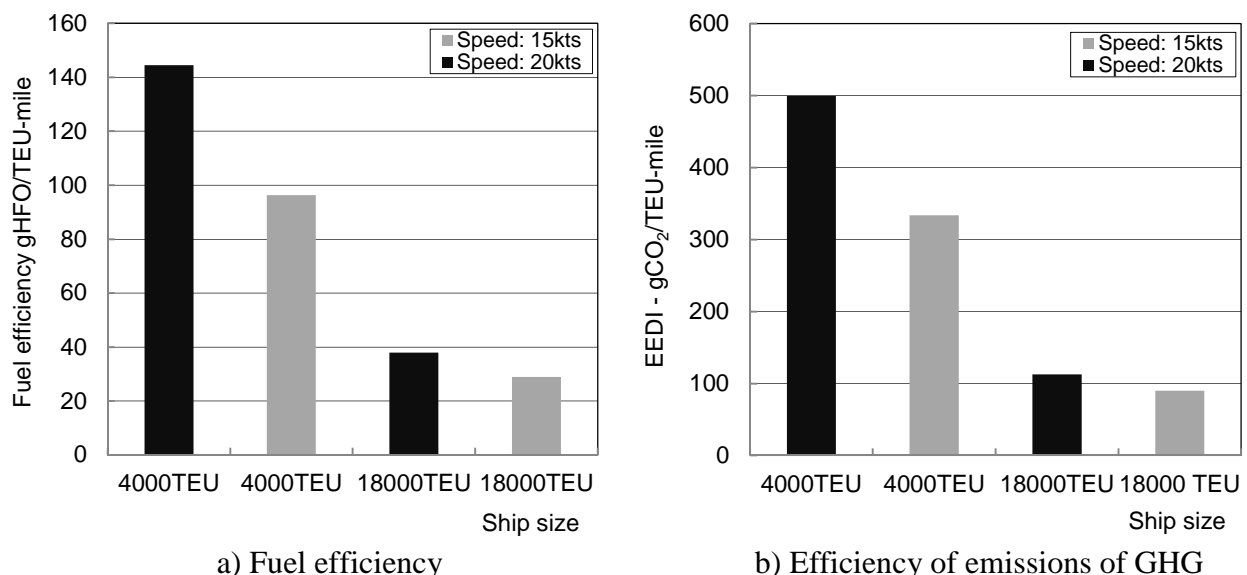
Table 3 Structure of the total cost of given supply chain: - The inventory cost during loading + unloading containers (TEUs) included

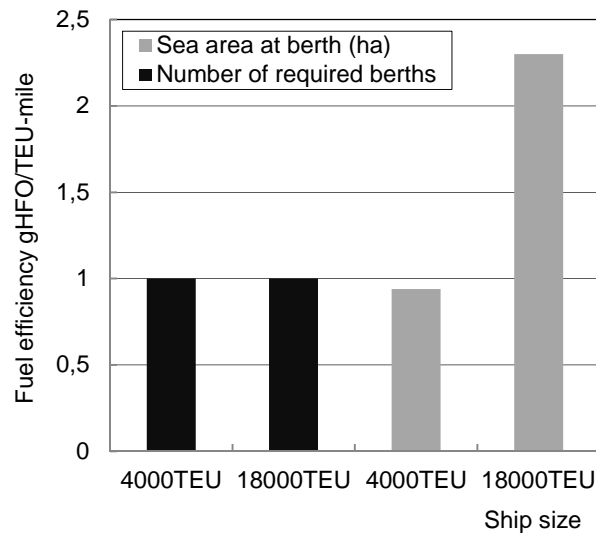
<u>Operating characteristics</u>	<u>Container ship capacity (TEU)</u>		
	<u>4000</u>	<u>18000</u>	<u>18000</u>
Loading/Unloading rate (TEU/h)	92/94	92/94	215/215
Operating speed (kts)	20/15	20/15	20/15
<u>Cost component (%)</u>			
Inventory	24/36	69/75	56/64
Handling	14/18	16/17	24/23
Transport	62/46	15/8	20/13

As can be seen, by excluding the inventory cost during collecting and distributing of containers (TEUs) at both ports, the share of this cost substantively decreases and the share of transport cost increases independently on the class of ship fleet serving the chain. However, the share of the former (inventory) cost remains much higher and the share of the latter (transport) cost remains much lower in case when the chain is served by the fleet of mega ships than in case when it is served by its smaller counterpart. In this case, reducing of the ships' operating speed also contributes to increasing of the share of inventory cost in the total chain's cost.

4.3.3 Environmental performances

The environmental performances of the given supply chain such as the fuel and emissions of GHG efficiency and use of land/space are shown in Figure 9 a, b, c, respectively. Figure 9a shows that the fleet of mega ships is for about 3.5 ad 4 times more fuel efficient than its counterpart of smaller ships if the slow and the super slow steaming speed is applied, respectively. At the fleet of smaller ships, changing from the slow (20kts) to the supper slow (15kts) steaming speed improves the fuel efficiency for about 50%. At its mega counterpart, these fuel efficiency improvements are for about 30%. Figure 9b shows the very similar relative relationships between the efficiency of emissions of GHG (CO₂) (i.e., EEDI – Energy Efficiency Design Index) of both ship fleets (LR, 2011). The fleet of mega ships is again much more efficient, but with lower relative gains achieved by reducing the operating/cruising speed. Figure 9c shows that only a single berth is needed at each hub port at both ends of the given chain to accommodate the ship(s) of either class operating under the above-mentioned service frequencies (Figure 7a). However, each mega ship(s) occupies for about 2.5 times larger area of sea near the berth than its smaller counterpart, which is intuitively expected.





c) Occupied space

Figure 9 Environmental performances of the given supply chain

4.3.5 Social performances

The social performances reflecting in some sense safety of the given supply chain such as the cost of risk of loss of ship in an accident are shown in Figure 10. As mentioned above, this cost of risk is based on the ship’s insurance premium and probability of an accident during the year causing the ship’s loss (The insurance premium is about €105 million for the mega ship and about € 37 million for the smaller ship (<http://www.lloydslist.com/>). As can be seen, depending on the operating/cruising speed influencing the required ship fleet size (Figure 7b), this cost of risk of loss are higher for about 13-14% at the smaller than at the mega ship fleet. This is because despite the insurance premium for the smaller ship(s) is lower for about 2.8.times than that for the mega ship(s), the fleet size of the former is greater for about 3.2-3.4 times than that of the latter.

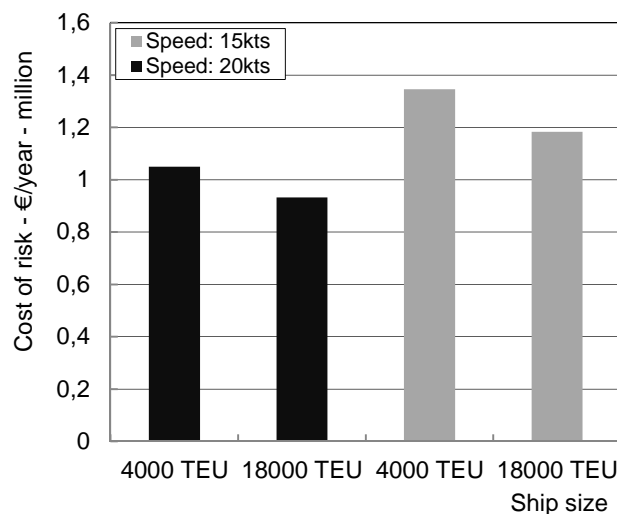


Figure 10 Social performances of the given supply chain – the cost of risk of loss of ship in an accident

5 CONCLUSIONS

This paper has developed the analytical models of operational, economic, environmental, and social performances of the supply chain(s) served by different classes of the freight transport vehicles including the mega ones. The infrastructural and technical/technological performances of the chain(s) have assumed to be given. The models have been applied to the case of the intercontinental supply chain served by the liner shipping according to the specified scenarios of exclusively using: i) nominal container ships (i.e., the Panamax class of the capacity of 4000TEU (Twenty Foot Equivalent Units)), and ii) the mega container ships (i.e., the Triple E Class of the capacity of 18000TEU). The results from application of the models have shown the following effects of using the fleet of mega container ships on the chain's performances in the given case:

Infrastructural and technical/technological performances

- Implicitly and/or explicitly used as inputs to the models of other performances of given supply chain.

Operational performances

- Lower service frequency of mega ships for transporting given volume of goods/freight shipments (i.e., containers – TEUs) during the specified period of time;
- Smaller required fleet of mega ships to serve the chain(s), i.e., deliver given volume(s) of freight/goods shipments (containers – TEUs) at the specified service frequency during the specified period of time; and
- Higher technical productivity of mega ship(s) at given operating speed but also highly sensitive to changing of that speed(s);

Economic performances

- Significantly lower transport (operational) cost of mega ship(s); and
- Substantively higher the average total cost of the chain served by mega ships due to dominance of the inventory cost, which otherwise can be reduced by speeding up the collection, loading, unloading, and distribution (i.e., handling) of goods/freight shipments (containers - TEUs) at the chain's hubs (This (inventory) cost tend to increase by reducing the operating speed of the ship(s) of either class).

Environmental performances

- Significantly higher relative efficiency of the fuel consumption and related emissions of GHG (Green House Gases) of mega ships, which could be further improved by reducing operating speed, but on the account of increasing the inventory cost of goods/freight shipments (containers – TEUs) and the required fleet size needed to serve the chain at the specified service frequency. and
- Larger area at sea at berths and the land occupied by berths needed for accommodating mega ships in ports; however, the smaller number of berths required due to the lower service frequency of mega ships and despite longer berth's occupancy time(s).

Social performances

- Lower cost of risk of loss of ship in an accident mainly due to the smaller fleet and despite much higher insurance premium per single mega ship; reducing speed to improve the

environmental efficiency requires the larger fleet of all ship classes, which consequently causes higher cost of risk of loss of ship.

Regarding the above mentioned facts based on the given case, it could be generally said that the mega freight transport vehicles can influence the performances of supply chain(s) in the relative and absolute terms, both generally positively and negatively:

The relative positive influence implies the lower service frequency and consequently smaller deployed vehicle fleet, the lower vehicle's operating cost due to economies of scale, the higher relative fuel efficiency and emissions of GHG, the smaller area of land/space taken for parking, and the lower cost of risk of loss of a vehicle of the smaller fleet.

The relative negative influence implies inherently the very high inventory costs of goods/freight shipments during handling of mega vehicles at the chain's hubs, which increase the chain's total costs, greater area of land/space taken for parking, and higher cost of risk of loss of a single vehicle.

In the absolute terms, the mega vehicles generally worsen the above-mentioned performances of the supply chain(s) served under given conditions mainly through raising its total (inventory, handling, and transport) cost, energy (fuel) consumption and related emissions of GHG, land used/taken, and the cost of risk of loss of a vehicle in an accident.

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