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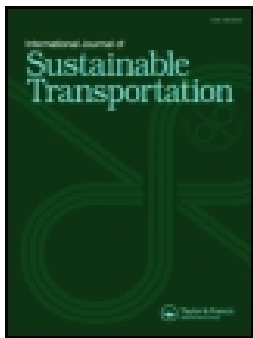
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Analysis, modeling, and assessing performances of supply chains served by long-distance freight transport corridors

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ABSTRACT

This article deals with an analysis, modeling, and assessing performances of supply chains served by long-distance intercontinental intermodal rail/road- and sea-shipping freight transport corridor(s). For such a purpose, the supply chains are defined and the methodology for assessing their performances under given conditions is developed. The methodology consists of the analytical models of indicators of the operational, economic, environmental and social performances of particular corridors and corresponding supply chains assumed to be dependent on the infrastructural and technical/technological capabilities. The models of particular indicators have been applied according to “what-if” scenario approach to assessing performances of the long-distance intercontinental inland and maritime freight transport corridors spreading between China and Europe in the scope of the “Silk Road Economic Belt” and “A New Maritime Silk Road” policy initiative. The results prove that the intermodal inland rail/road alternative could act as a serious competitive alternative to its maritime deep-sea counterpart under given conditions. Nevertheless, in order to realize the opportunities, large investments in the inland rail/road infrastructure are required to appropriately connect China with Europe.

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Supply chains; long-distance corridors; performances; indicators; models

1. Introduction



The aim of freight transport policy has been to accommodate the growing freight transport demand in a sustainable way (Commission of the European Communities, 2011). One of the measures to achieve this aim has been to increase the market share of rail and intermodal rail/road transport by implementing the concept of freight transport corridors throughout Europe and between Asia and Europe. These corridors have been expected to serve the supply chains by attracting more voluminous freight transport demand primarily from road at the continental (European) and from deep-sea shipping at the intercontinental (Asia-Europe) scale.

At the intercontinental scale, policies initially focused on stimulating investments, which mostly related to network projects (nodes and links) of rail transport and deep-sea shipping (ports). However, starting from the 2000s, the attention has shifted towards transport corridors and missing links and nodes along them (see e.g. Zunder et al., 2016). In particular, the Chinese and European transport policies have strived to improve the competitiveness of rail and intermodal rail/road freight transport by investing in rail infrastructure. However, unless countless efforts (business, policy, scientific) only limited effects have been achieved (Wiegman & Donders, 2007). Namely, the land-links between Asia and Europe—among the oldest trade routes in the world—have not been used for any more substantive intercontinental

commercial trade of containerized cargo. Contrary, the freight transport services carried out by deep-sea transport has been continuously growing over time as shown in Figure 1(a,b).

However, endeavors to strengthen the ties between the two continents have continued. Most recently, in 2015, the policy package OBOR (“One Belt & One Road”) initiative was approved by the Chinese State Council. The package consists of the “Silk Road Economic Belt” and “A New Maritime Silk Road” initiative aiming at creating a highly integrated, cooperative, and mutually beneficial set of land-based and maritime transport corridors between Asian and European markets. The main freight transport policies aim at providing sufficient capacity, interoperability reliability, availability, safety, environmental and social friendliness of transport and other activities carried out within particular supply chains, which appears particularly important for the inland corridors within “Silk Road Economic Belt” initiative (Bureika et al., 2016).

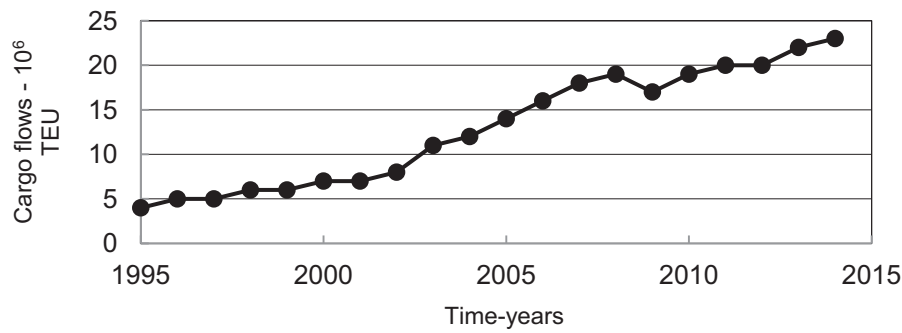
This article investigates if the supply chains regarding their performances considered from the aspects of particular stakeholders could be more attractive, if served by long-distance intermodal Euro-Asian rail/road freight transport corridor instead of the currently dominating deep-sea shipping Suez-Canal corridor. Therefore, in addition to this introductory section, Section 2 describes the concept of long-distance freight transport corridors serving supply chains. Section 3 develops a

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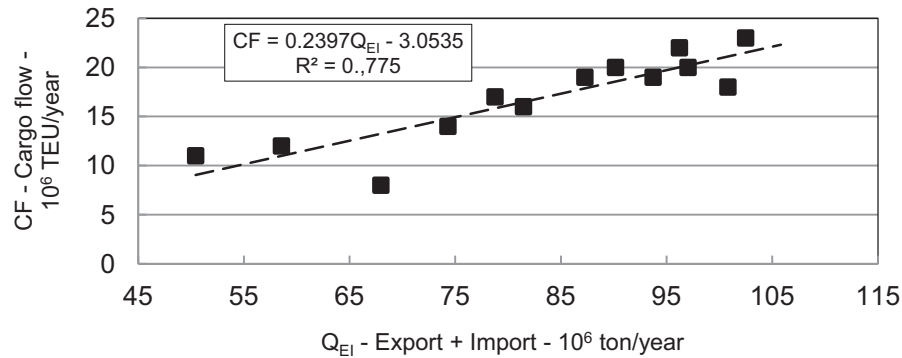
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(a) Development of containerized cargo flows over time (Period: 1995–2014)



(b) Relationship between the containerized cargo flows and the volumes of trade (Period: 2002–2015)

Figure 1. Characteristics of the deep-sea containerized cargo flows Europe–Asia–Europe (United Nations Conference on Trade and Development, 2016; <http://ec.europa.eu/trade/policy/countries-and-regions/statistics/>). (a) Development of containerized cargo flows over time (period: 1995–2014). (b) Relationship between the containerized cargo flows and the volumes of trade (period: 2002–2015).

methodology consisting of the models of performance indicators of supply chains. Section 4 presents an application of the proposed methodology (i.e. performance indicators to the above mentioned case corridors serving an equivalent supply chain). The last section summarizes some conclusions.

2. Freight transport corridors and supply chains they serve

2.1. Intermodal rail and rail/road freight transport corridors

Rail corridors are entities with the linear spatial layout spreading longitudinally over long distance through different regions, countries, and sometimes continents. The corridor's transport infrastructure includes one or more pairs of bi-directional rail tracks connecting the sequentially located rail/road intermodal freight terminals. These terminals provide container exchange of freight shipments of different size—weight/volume between road and rail, and vice versa. The standardized units enable carrying out transport services between particular terminals by intermodal block trains. Figure 2 shows the example of the relationship between the gross weight and length of container trains in Europe (Janić, 2008). As can be seen, the gross weight of these trains increases linearly with their length. In the long-distance intercontinental corridors between Asia and Europe, the intermodal container trains of length of 800 m, 1000 m, and even longer are expected to operate. They are to be composed of 38 or 48 rail flat

wagons, respectively, weighting in total about 2400–2800 tons. If pulled by one or two 6 MW locomotives, these trains would be able to operate at a maximum speed of 65–70 and 90 km/h, respectively. The average commercial speed of Long Intermodal Freight Trains (LIFTs) between the distant intermodal terminals will not be higher than 20–40 km/h (Janić, 2008).

2.2. The long-distance deep-sea freight transport corridors

These are linear transport service configurations along the main deep-sea routes connecting ports located in different countries on the same and/or different continents. The ports are generally equipped with dedicated terminals enabling exchange of containerized freight shipments. The transport services are carried out by container ships of different capacity, which has been continuously increasing over the past five decades as shown in Figure 3. As can be seen, the capacity of container ships has been increasing more than proportionally over the observed period of time. They have been running between ports at “slow steaming” and “super slow steaming” speed of 20 and 15 kt, respectively (kt: knot; 1 kt = 1.852 km/h) (WSC, 2015).

2.3. Supply chains

2.3.1. Components

Both corridor types can serve supply chains along them. A supply chain can be considered as an integrated hub-and-spoke

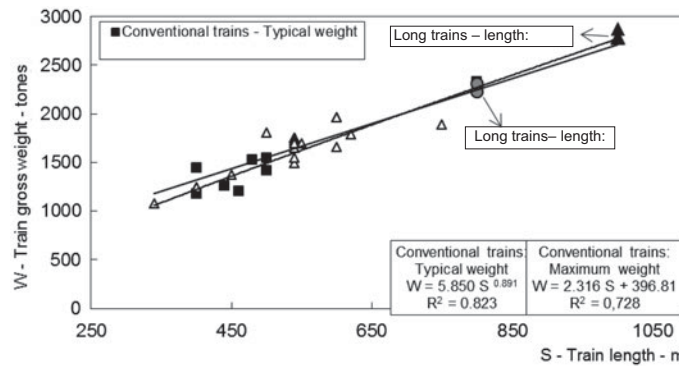


Figure 2. The example of the relationship between gross weight on length of intermodal container trains in Europe (Janić, 2008).

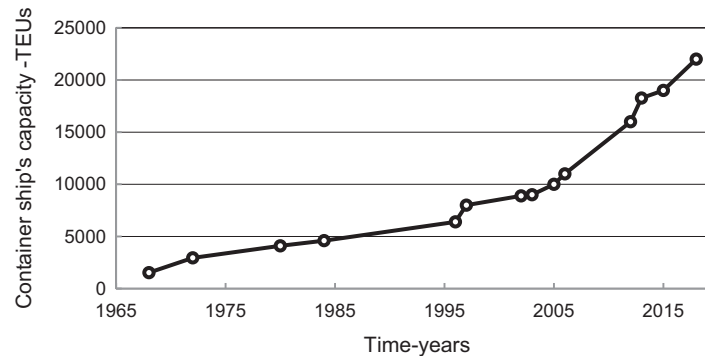


Figure 3. Development of capacity of deep-sea container ships (<http://www.container-transportation.com/container-ships.html>).

physical network producing, handling, transporting, and consuming given volumes of freight shipments under given conditions. The main network hubs are usually large rail and intermodal (rail/road) terminals and the sea-port terminals sequentially located along the corresponding corridors. As the ultimate origins called “hub suppliers”, they handle containerized freight shipments after being collected from users-shippers called “spoke suppliers”. As the ultimate destinations called “hub customers”, freight shipments are handled before being distributed to users-receivers called the “spoke customers”. Both freight shippers and receivers are located in the gravitational areas of the corresponding hubs mutually connected by ground access transport systems such as primarily road in the intermodal rail/road and road, and rail in the deep-sea case. The simplified spatial configuration of a supply chain(s) served by any of the freight transport corridors can be represented as a H-S (Hub-and-Spoke) transport network is shown in Figure 4(a,b) (Janić, 2016). As can be seen, at the origin side of freight shipments, the spoke suppliers representing the actual shippers “feed” the hub supplier (i). At the destination side of freight shipments, the hub customer (j) feeds the spoke customers representing the actual receivers. Under such circumstances, some inventories of freight shipments within the chain can happen at the hub supplier, the hub customer, and along the route(s) between them. Figure 4(a) shows the case of exclusive and Figure 4(b) the case of simultaneous collecting and loading of 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 its loading begins, and the entire shipment is unloaded before its distribution begins. “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 carried out at the same time. In both cases, some storage time of shipments is also considered.

2.3.2. Capabilities and performances

Substantive scientific and consultancy related research on freight transport and supply chains they serve has already been carried out (see e.g. Aditjandra et al. 2016). To the authors’ knowledge, the research explicitly dealing with the indicators of performances of supply chains served by different freight transport corridors and their systematic performance comparison is still lacking. This article intends to partially fill this gap. The supply chains served by freight transport corridors are generally characterized by infrastructural (i) and technical (ii) capabilities, and by operational (iii), economical (iv), and environmental and social (v) performances as shown in Figure 5.

(A) Infrastructural and technical/technological capabilities.

Infrastructural and technical/technological performances generally relate to the physical, constructive, technical and technological features of the infrastructure: railway lines and intermodal terminals; the rolling stock (truck, trains and container ships), and the supporting facilities and equipment (transshipment facilities in the corresponding terminals of both corridors, and signaling and traction system of the intermodal rail/road corridor). These corridor capabilities influence the performance of supply chains served by the freight transport corridors.

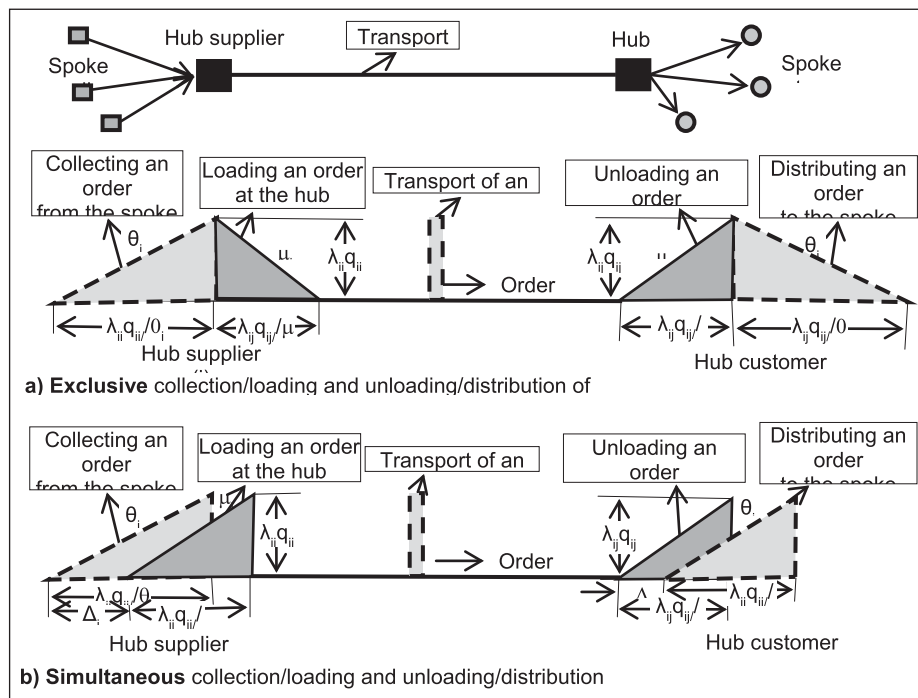


Figure 4. Simplified scheme of supply chain served by any of the corridors considered (Janic, 2016).

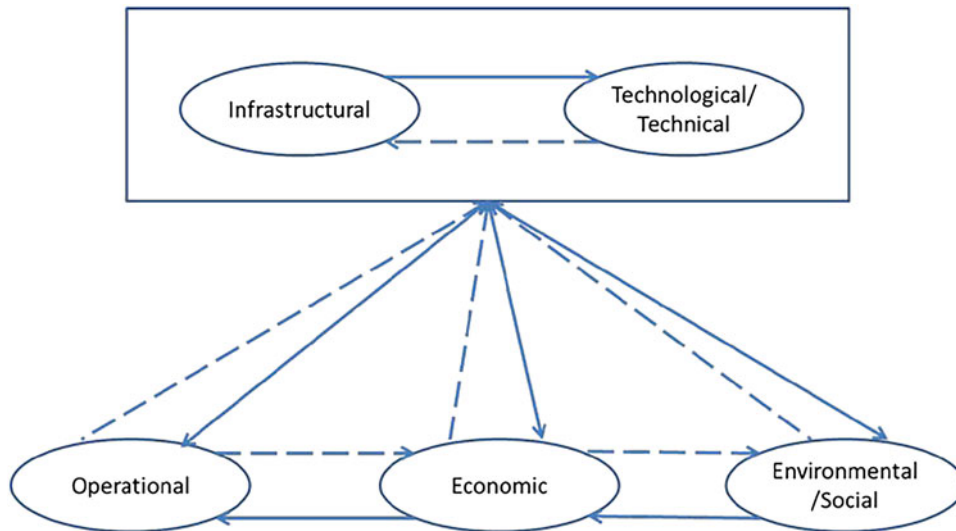


Figure 5. A simplified scheme of performances of a supply chain served by given freight transport corridor(s) and their possible interrelationships. Source: Based on Witte et al. (2012).

(B) Operational performances. Operational performances include demand, capacity, and their relationship, i.e. quality of services, fleet size, and technical productivity of systems serving supply chains in both corridor types. This mainly focuses on understanding the relationships between the transport and logistics operations and potential improvements through the freight shipment delivery speed, service quality, operating costs, use of facilities and equipment, and energy savings (Tseng et al., 2005), modeling the performances of spatial and operational configurations of the freight collection/distribution networks (Janić 2005), and understanding the potential interactions between the location of the European manufacturing industry and related services (European Commission, 1999). Several researches have been performed into model

choice and modal shift in relation to supply chains in corridors. Regmi and Hanaoka (2015) assessed the modal shift and emissions along a freight transport corridor between Laos and Thailand. Their results show that reduction of emissions of CO₂ of about 30% can be expected by mode shift to rail compared to a business-as-usual scenario.

The general performances of supply chain(s) focuses on understanding the relationship between the supply chain management (SCM) practice and the supply chain performances (SCP). In such a context the performances and their measures have focused on the strategic, operational, and tactical level (Gunasekaran et al., 2004), reliability, responsiveness, cost and assets (Huang et al., 2005; Lai et al., 2002), the overall chains' goals (Otto and Kotzab, 2003), instruments for measuring

collaboration between the chain's suppliers and retailers (Simatupang & Sridharan, 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 includes estimating performances of the supply chain(s) under uncertainty by applying fuzzy logic (Olugu and Wong, 2009). As well, the criteria for developing the SCP measurement systems (PMS) in addition to identifying barriers to their implementation has been carried out (Fauske et al., 2006). The role and influence of transport operations on the performances of supply chain(s) mainly focuses on understanding the relationships between the transport and logistics operations and potential improvements through the freight shipment(s) delivery speed, quality of service, operating costs, use of facilities and equipment, and energy savings (Tseng et al., 2005), modeling the performances of various spatial and operational configurations of the goods/freight collection/distribution networks (Janić 2005), and understanding the potential interactions between the location of the European manufacturing industry, related services, and logistics and freight transport (European Commission, 1999).

(C) Economic performances. Economic performances generally include costs, revenues, and results. Janić (2008) assessed the performance of the European LFTs. The analytical models to compare the full costs (internal and external) of rail and truck services were developed and their application proved that the long trains could have potential to improve the performance of intermodal rail freight versus the truck-only transport. Márquez and Cantillo (2013) evaluate strategic freight transport corridors including external costs. They develop a freight transport model that includes external cost. Their main conclusion is that for roads external costs are equal to 37% of internal costs, for railways 12% and for Inland Water Way (IWW) 1%. Wiegman and Konings (2015) evaluated economic performances of different supply chains in the Rhine corridor. Their analysis showed that in many cases Inland Waterway Transport (IWT) can be competitive to road transport.

(D) Environmental and social performances. Environmental and social performances generally embrace impacts of both corridors serving given supply chain(s) on the environment and society in terms of the energy/fuel consumption and related emissions of GHG (Green House Gases), land use, noise, congestion, and traffic incidents. Patterson et al. (2008) analyzed the potential for premium-intermodal services to reduce freight CO₂ emissions in the Quebec City–Windsor corridor. Their main conclusion was that a 20% increase in the price of truck-only relative to intermodal services would be sufficient to overcome shipper bias towards intermodal carriage. Janić and Vleugel (2012) developed a method to analyze and estimate savings in externalities that could be achieved by substituting truck with rail freight services in a given Trans-European freight transport corridor. The application of the method indicated that substantive savings in particular externalities could be achieved. Nocera and Cavallaro (2016) proposed a methodology based on a Well-To-Wheel quantification and an economic valuation deriving

from a meta-regression. The application of the methodology to the given case indicated that potential savings of the emissions of CO₂ up to 600,000 tons and €38 million could be achieved by the year 2030. The sustainability (i.e. greening) of supply chain(s) mainly focuses on defining the management of green supply chain(s) means by integrating environment-thinking into SCM, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumer, and the end-of-life management of the product after its use (Srivastava, 2007; Stevels, 2002). In addition, this body of research also investigates the potential initiatives, driving forces, and barriers to implementing “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 could all lead to the achievement of sustainable (green) logistics and SCM (Evangelista et al., 2010; World Economic Forum, 2009). In order to compare the above-mentioned performances of supply chains if served by different freight transport corridors, the indicators are modeled below.

3. Methodology for performance assessment of supply chains served by long-distance freight transport corridors

3.1. Assumptions

The methodology is based on the following assumptions:

- A given supply chain with specified freight volumes is served by corridors operating as independent alternatives according to “what-if” operating scenario;
- The chain performance indicators are considered for a specified time period;
- The indicators of chain's infrastructural and technical/technological capabilities are analyzed in the qualitative way. The analytical models are developed for indicators of the chain's operational, economic, environmental and social performances; and
- Indicators and their influencing factors in the models are considered as constant parameters rather than stochastic variables for the given time period.

3.2. Capabilities of supply chains served by particular corridors

3.2.1. Physical/spatial or infrastructural capabilities

Based on the discussed literature above and the available data, the indicators of physical/spatial or infrastructural capabilities of a given supply chains are considered to be the chain's and route length, accessibility, area coverage, and infrastructure density.

- *Chain's length:* Distance between the most remote hub supplier and hub customer measured along the connecting line routes
- *Route length:* Distance between any two chain's hub supplier and hub customer as the ultimate origin and

destination of the TEU¹ shipments and related inter-hub transport services

- **Accessibility:** Ratio between the number of chain's hub suppliers and hub customers (i.e. terminals) and the chain's length. Relevant for users, i.e. spoke suppliers-shippers and spoke customers-receivers of TEUs, since it represents the quality of spatial accessibility of the chain's inter-hub transport services
- **Area coverage:** Sum of gravitational areas of the individual hub suppliers and hub customers (i.e. terminals) along the chain's length. As a measure of the spatial availability of services around the entire area around the chain(s), this is relevant for shippers and receivers of TEUs
- **Infrastructure density:** Ratio between the length of a chain and the size of its coverage area. In the chain served by inter-modal rail/road corridor, it is a continuous strip of land handling the corridor's infrastructure. In the chain served by sea-shipping corridor, it is the sum of gravitational areas of the hub suppliers and hub customers (i.e. ports).

3.2.2. Technical/technological capabilities

The indicators of technical/technological capabilities of a given chain served by a corridor are the propulsion systems, interoperability, vehicle characteristics, and terminal characteristics as the hub suppliers and the hub customers.

- **Propulsion systems:** Number of differently powered rolling stocks performing transport services within a chain. In the chain served by the rail corridor, the trains are pulled by diesel or electric locomotives. When the routes in the chain are not electrified, the necessary consequence is

- **Interoperability** in the chain served by the rail corridor is expressed by the number of different propulsion systems changed per the country's border crossings. This indicator is relevant for rail operators while planning deployment of multi-system engines. In the chain served by sea-shipping corridor this may refer to flexibility of the port terminals to handle different ship sizes.
- **Characteristics of vehicles:** The length/weight, payload capacity, and technical speed. In the chain served by the rail corridor they relate to the individual trains and are conditioned by the characteristics of infrastructure and traffic management systems along routes. In the chain served by sea-shipping corridor they relate to the ships used.
- **Characteristics of terminals as the hub suppliers and the hub customers:** Capacity and utilization of the terminal transshipment facilities and equipment. These are relevant for the terminal operators in both corridors while offering their services to both rail and sea-shipping transport operators.

3.4. The models of performance indicators of supply chains served by corridors

3.4.1. Operational performance

The indicators of operational performances of the given supply chain served by the above-mentioned freight transport corridors are: (a) transport service frequency: (i) serving exclusively the given volumes of freight transport demand, and (ii) enabling the specified services during the chain's production/consumption cycle; (b) size of deployed vehicle fleet; and (c) (technical) productivity (Janic, 2016). In modeling these indicators, the following notation is used:

TU	is time unit (h, day)
T	is duration of the supply chain's production/consumption cycle (TU)
$Q_{ij}(\tau)$	is the volume of freight shipments to be transported from the hub supplier (i) to the hub customer (j) during the chain's production/consumption cycle (τ) [(tons or TEUs)/TU]
λ_{ij}	is the average load factor of a vehicle serving the supply chain (ij) (-)
q_{ij}	is the average payload capacity of a vehicle serving the supply chain (ij) [(tons or TEUs)/vehicle]
$h_{ij}(\tau)$	is the average time between the vehicle departures between the hub supplier (i) and the hub customer (j) during time (τ) (TU)
τ_{ij}, τ_{ji}	is the average time a vehicle spends operating in the direction (ij) and (ji), respectively, of a given supply chain (TU/vehicle)
Δ_{i1}, Δ_{j1}	is the time between starting a vehicle's loading at the hub supplier (i) and its unloading at the hub customer (j), respectively (TU)
Δ_{j2}, Δ_{i2}	is the time between starting a vehicle's loading at the hub customer (j) and its unloading at the hub supplier (i), respectively (TU)
d_{ij}, d_{ji}	is the length of the chain's route, i.e. the distance between the hub supplier (i) and the hub customer (j), and vice versa, respectively, measured along the transport link connecting them (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 kt (knot); 1 kt = 1 nm/h; nm: nautical mile = 1.852 km]
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 back, respectively (TU)
μ_{i1}, μ_{j1}	is the loading and unloading rate of a vehicle at the hub supplier (i) and at the hub customer (j), respectively (tons, m ³ or TEU/TU)
p_{i1}, p_{j1}	is the proportion of the vehicle's loading and unloading rate used at the hub supplier (i) and at the hub customer (j), respectively ($p_{i1}, p_{j1} \leq 1.0$)
μ_{j2}, μ_{i2}	is the loading and unloading rate of a vehicle at the hub customer (j) and at the hub supplier (i), respectively (tons, m ³ or TEU/TU)
p_{j2}, p_{i2}	is the proportion of the vehicle loading and unloading rate used at the hub customer (j) and at the hub supplier (i), respectively ($p_{j2}, p_{i2} \leq 1.0$)

changing the engines usually at borders of particular countries. In the chain served by sea-shipping corridor this is characterized by the power of ships' engines mainly influenced by their size.

a) Transport service frequency (dep/TU):

- The service frequency set up given volumes of freight transport demand during the specified period of time in the supply chain (ij) is determined as follows:

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

¹TEU (Twenty-foot Equivalent Unit) is an unit of cargo capacity often used to express the capacity of container ships and container terminals (https://en.wikipedia.org/wiki/Twenty-foot_equivalent_unit).

Equation (1a1) indicates that the service frequency is proportional to the volumes of freight shipments to be transported from the hub supplier (i) to the hub customer (j) during the chain's production/consumption cycle (τ) and inversely proportional to the average vehicle size and load factor.

- ii. The frequency set up to enable the specified services in the supply given chain (ij) during its operating cycle is as follows:

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

Equation (1a2) implies that the freight shipments are always available and uniformly distributed over the specified time-period and thus the service frequency can be adjusted to serve them in regular time intervals. From Equation (1a2), the total volume of freight shipments, which can be transported in the supply chain (ij) during time (τ) is determined as:

$$Q_{ij}^*(\tau) = \left[\min(f_{ij}(\tau); f_{ij}^*(\tau)) \right] \cdot (\lambda_{ij} \cdot q_{ij}) \quad (1a3)$$

- b) The size of vehicle fleet (vehicles/cycle):

Based on Equations (1a1,1a2), the size of vehicle fleet can be estimated as follows:

$$N_{ij}(\tau) = \left[\min(f_{ij}(\tau); f_{ij}^*(\tau)) \right] \cdot t_{ij/ji}(d_{ij}, d_{ji}) \quad (1b1)$$

If each vehicle operates in the chain (ij) and (ji), its average turnaround time $t_{ij/ji}(d_{ij}, d_{ji})$ (TU/veh) in Equation (1b1) can be estimated as follows:

$$t_{ij/ji}(d_{ij}, d_{ji}) = \tau_{ij} + \tau_{ji} = \Delta_{i1} + \frac{\lambda_{ij} \cdot q_{ij}}{p_{i1} \cdot \mu_{i1}} + \frac{d_{ij}}{v_{ij}(d_{ij})} + D_{ij} + \Delta_{j1} + \frac{\lambda_{ji} \cdot q_{ji}}{p_{j2} \cdot \mu_{j2}} + \frac{d_{ji}}{v_{ji}(d_{ji})} + D_{ji} + \Delta_{i2} + \frac{\lambda_{ji} \cdot q_{ji}}{p_{i2} \cdot \mu_{i2}} \quad (1b2)$$

The vehicle's (un)loading rates μ_{i1} , μ_{j1} , μ_{j2} , and μ_{i2} in Equation (1b2) depend on the number of engaged loading/unloading devices (usually cranes) and their capacity. In addition, Equation (1b2) 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 any such impact lasts a prolonged period of time, then Equation (1b2) indicates that a larger vehicle fleet will be needed to serve the supply chain(s). In this respect, it is assumed that in the hub regions (such as e.g. Shanghai or Rotterdam) there are sufficient volumes available enabling the running of services in both directions.

- c) (Technical) productivity (TEU-km/TU or ton-km/TU):

Based on Equation (1a3,1b2) (after being appropriately modified), the (technical) productivity of the given supply chain (ij) is as follows:

$$TP_{ij}(\tau) = Q_{ij}^*(\tau) \cdot \left(\frac{d_{ij}}{t_{ij}(d_{ij})} \right) = Q_{ij}^*(\tau) \cdot v_{ij}(d_{ij}) \quad (1c1)$$

Equation (1c1) indicates that the (technical) productivity of the supply chain is proportional to the product of the volumes of transported freight shipments and the average vehicle speed during its turnaround time.

3.4.2. Economic performances

The indicators of economic performances of the given supply chains are: (a) inventory, (b) handling, and (c) transport (i) total and (ii) average costs of freight shipment(s) served by the chain. The case when the size of freight shipment corresponds to the vehicle payload capacity is considered. In modeling of the above-mentioned indicators, the following notation is used:

θ_i, θ_j	is the rate of collecting and distributing freight shipments at the hub supplier (i) and the hub customer (j), respectively (ton/TU or TEU/TU);
$c_i, c_j, c_{ij}(d_{ij}; \lambda_{ij} q_{ij})$	is the average handling (loading/unloading/transshipment) cost of a freight shipment at the hub supplier (i), the hub customer (j), and transport cost, respectively (€/ton or €/TEU; €/ton-km or €/TEU-km); and
$\alpha_i, \alpha_{ij}, \alpha_j$	is the average cost of freight shipment inventory time at the hub supplier (i), in transportation, and at the hub customer (j), respectively (€/ton-TU or €/TEU-TU).

- a) Inventory costs (€):

The inventory cost of a freight shipment in the chain (ij) is estimated as follows:

$$C_{ij/INV}(\lambda_{ij} q_{ij}) = IT_i(\lambda_{ij} q_{ij}) \cdot \alpha_i + (\lambda_{ij} \cdot q_{ij}) \cdot \left(\frac{d_{ij}}{v_{ij}(d_{ij})} + D_{ij} \right) \cdot \alpha_{ij} + IT_j(\lambda_{ij} \cdot q_{ij}) \cdot \alpha_j \quad (2a1)$$

The first and third term in Equation (2a1) represent the inventory cost of a freight shipment at the hub supplier (i) and at the hub customer (j), respectively. The second term represents the inventory, i.e. the freight shipment's cost of time while in transportation between the hubs (i) and (j). In addition, from Figure 1, the inventory time of freight shipment in Equation (2a1) at the hubs (i) and (j), respectively, is determined for the cases a) and b) on Figure 4 as follows:

$$IT_i(\lambda_{ij} q_{ij}) =$$

$$\left\{ \begin{array}{l} \frac{1}{2}(\lambda_{ij} q_{ij})^2 \cdot \left[\frac{1}{\theta_i} + \frac{1}{p_i \cdot \mu_i} \right] \text{ if a) } \\ \max \left\{ 0; (\lambda_{ij} q_{ij})^2 \cdot \left(\frac{1}{p_i \cdot \mu_i} - \frac{1}{2 \cdot \theta_i} \right) + (\lambda_{ij} q_{ij}) \cdot \Delta_{i1} \right\} \text{ if b) } \end{array} \right\} \quad (2a2)$$

and analogously

$$IT_j(\lambda_{ij} q_{ij}) =$$

$$\left\{ \begin{array}{l} \frac{1}{2}(\lambda_{ij} q_{ij})^2 \cdot \left[\frac{1}{\theta_j} + \frac{1}{p_j \cdot \mu_j} \right] \text{ if a) } \\ \max \left\{ 0; (\lambda_{ij} q_{ij})^2 \cdot \left(\frac{1}{p_j \cdot \mu_j} - \frac{1}{2 \cdot \theta_j} \right) + (\lambda_{ij} q_{ij}) \cdot \Delta_{j1} \right\} \text{ if b) } \end{array} \right\} \quad (2a3)$$

- b) Handling and transport costs (€):

The handling and transport costs per single shipment in the supply chain (ij) are as follows:

$$C_{ij/H-TRA}(\lambda_{ij} q_{ij}) = c_i \cdot (\lambda_{ij} q_{ij}) + c_{ij}(d_{ij}; \lambda_{ij} q_{ij}) \cdot (\lambda_{ij} q_{ij} \cdot d_{ij} + c_j \cdot (\lambda_{ij} q_{ij})) \quad (2b1)$$

The first and third term in Equation (2c1) represent the cost of handling, and the second term the transport cost. In case of the containerized freight shipments, the transport cost

can also take into account the cost of collecting and distributing them to and from the hub supplier and hub customer.

c) Total (inventory \pm handling \pm transport) costs (€):

From Equations (2a1, 2, 3 and 2b1), the total cost of processing freight shipment in the supply chain (ij) is estimated as the sum of costs of particular phases as follows:

$$C_{ij}(\lambda_{ij}q_{ij}) = C_{ij/INV}(\lambda_{ij}q_{ij}) + C_{ij/H-TRA}(\lambda_{ij}q_{ij}) \quad (2c1)$$

(d) Average total costs (€/ton-km or €/TEU-km)

From Equation (2c1), the average unit cost of processing freight shipment in the chain (ij) is equal as follows:

$$\bar{c}_{ij}(\lambda_{ij}q_{ij}) = C_{ij}(\lambda_{ij}q_{ij}) / [(\lambda_{ij}q_{ij}) \cdot d_{ij}] \quad (2c2)$$

By replacing the size of shipment ($\lambda_{ij}q_{ij}$) with the actual volumes of freight shipments generated during the chain's production/consumption cycle (Q_{ij}), the economic performance indicators can be estimated from Equation (2).

3.4.3. Environmental and social performance

The indicators of environmental and social performance of the supply chain are considered to be: (a) the energy (fuel) consumption and related emissions of GHGs [Green House Gas(es)]; (b) land use; (c) noise; (d) congestion; and (e) the cost of an incident/accident (Janic & Vleugel, 2012). In modeling of the above-mentioned indicators, the following notation is used:

$FC[q_{ij};v_{ij}(d_{ij})]$	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}) (KWh/km, liter/km, ton/km);
e_k	is the emission rate of the (k)-th GHG from the consumed energy (fuel) of a vehicle serving the supply chain (ij) [kg of GHG/(KWh, liter, kg)];
K	is the number of various GHGs emitted from the consumed energy (fuel) by a vehicle serving the supply chain in direction (ij);
N, M	is the number of hub suppliers and hub consumers, respectively, in the supply chain served by the corridor;
A_i, A_j	is the average size of gravitational area of the hub supplier (i) and hub customer (j), respectively (km ²); and
b_{ij}, b_{ji}	is the average width of the land strip occupied by the transport infrastructure spreading between the hub supplier (i) and the hub customer (j), and vice versa, (km).
δ_{ij}	is a binary variable taking the value "1" if the supply chain (ij) is served by the inland freight transport corridor and the value "0", otherwise.
$L_{eq}(\gamma_{ij}, v_{ij})$	is noise of a passing vehicle at the speed (v_{ij}) and distance (γ_{ij}) (decibels: dBA);
v_{ij}	is the speed of a passing vehicle serving the supply chain (ij) (km/h); and
γ_{ij}, β_{ij}	shortest (right angle) and slant distance, respectively, between the noise source, i.e. moving vehicle serving the supply chain (ij), and the exposed observer (m);
$P_{ij}(\tau)$	is the probability of an accident causing the loss of a vehicle and its payload while serving the supply chain (ij) (probability of an event/TU); and

a) Energy (fuel) consumption and emissions of GHG (kWh, liter, ton):

The total energy (fuel) consumption, respectively, in the supply chain (ij) can be estimated from Equation (1a3) as follows:

$$FC_{ij}(\tau) = \left[\min(f_{ij}(\tau); f_{ij}^*(\tau)) \right] \cdot FC[q_{ij}; v_{ij}(d_{ij})] \cdot d_{ij} \quad (3a1)$$

From Equation (3a1), the average energy (fuel) consumption ((kWh, liter, ton)/ton-km or ((kWh, liter, ton)/TEU-km) can be estimated as follows:

$$\overline{FC_{ij}(\tau)} = FC_{ij}(\tau) / [Q_{ij}^*(\tau) \cdot d_{ij}] \quad (3a2)$$

The total quantity of emissions of GHGs (tons) based on Equation (3a1) are determined as follows:

$$EM_{ij}(\tau) = \sum_{k=1}^K FC_{ij}(\tau) \cdot e_k \quad (3b1)$$

The average emissions of GHGs (ton of GHG/(TEU-km or ton-km)) based on Equation (3a2) are determined as follows:

$$\overline{EM_{ij}(\tau)} = EM_{ij}(\tau) / [Q_{ij}^*(\tau) \cdot d_{ij}] \quad (3b2)$$

b) Land use (ha, km²):

This is represented by the land area used for settling down the chain's infrastructure including the hub supplier and the hub customer terminals and the transport infrastructure lines connecting them. This land area can be estimated as follows:

$$LU_{ij} = \sum_{i=1}^N A_i + \delta_{ij} \cdot \sum_{i=1}^N \sum_{j=1}^M (b_{ij} \cdot d_{ij} + b_{ji} \cdot d_{ji}) + \sum_{k=1}^M A_j \quad (3c1)$$

If the infrastructure occupying given land is already in place, the intensity of its use [(ton-TEU)/(ha or km)/TU] by the supply chain (ij) can be estimated, based on Equation (3c1), as follows:

$$ILU_{ij}(\tau) = Q_{ij}(\tau) / LU_{ij} \quad (3c2)$$

c) Noise

Noise is generally generated by the transport vehicles (trains, trucks) serving the supply chain while passing an exposed (close) population. In particular, the noise of trains connecting the main hubs along the corridor(s) mainly depends on the level generated by the source, i.e. a vehicle (train) moving at a certain speed at the certain (free of barriers) distance from the exposed observer (dBA) population. In the given supply chain (ij), this distance changes over time during the vehicle's passing by as follows:

$$\rho_{ij}^2(t) = (L_{ij}/2 + \beta_{ij} - v_{ij}t)^2 + \gamma_{ij}^2 \text{ for } 0 < t \leq (L_{ij} + 2\beta_{ij}/v_{ij}) \quad (4a1)$$

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

$$L_{eq}[\rho_{ij}(t), v_{ij}] = L_{eq}(\gamma_{ij}, v_{ij}) - 8.6562 \ln[\rho_{ij}(t)/\gamma_{ij}] \quad (4a2)$$

The second term in Equation (4a2) represents the noise attenuation over a barrier free area between the noise source and an exposed human. The noise from $f_{ij}(\tau)$ successive vehicles passing by during the time period (τ), is determined as follows:

$$L_{eq}[f_{ij}(\tau)] = 10 \log \sum_{r=1}^{f_{ij}(\tau)} 10^{\frac{L_{eq}[\rho_{ij}(t), v_{ij}]}{10}} \quad (4a3)$$

In addition, the noise from the vehicles-trucks carrying out collection and distribution of freight shipments can also

be considered in the similar way. The deep-sea ships operating between main hubs—port terminals—are excluded from this consideration due to their operations at the open sea. However, noise from collecting and distributing of freight shipments is reasonable to be considered around ports either if they are carried out by rail or road.

Congestion in the supply chain served by any of two corridors can happen at the hub supplier and hub customer. In the case of rail/road, incoming trucks can wait at the terminal entry gate for entering the terminal. The outgoing trains could be delayed if the outgoing line is too busy. At the hub consumer these now incoming trains can experience congestion due to the lack of terminal capacity. The outgoing trucks can also experience delays due to congestion at the terminal exit gate. In the case of deep-sea terminals, congestion can also happen at both landside and seaside of both hub supplier and hub customer. These delays are considered as included in the container inventory time at both ends of the chain.

(e) Risk of incidents/accidents

The perceived risk of vehicle loss (including its load) during the production/consumption cycle of supply chain (ij) is estimated as parameter $P_{ij}(\tau)$ from the relevant statistical data.

4. An application of the proposed methodology

4.1. Inputs

4.1.1. Geography of the supply chains served by freight transport corridors

The above-mentioned models of supply chain performances are applied to the case of the supply chain between North Europe and Far East Asia (China). This is served by either of the above-mentioned OBOR's corridor: "Silk Road Economic Belt": South intermodal rail/road corridor China-Central Asia-Russia-Europe; or "Existing and New Maritime Silk Road": South China Sea-Indian Ocean-Europe deep-sea container shipping corridor.² In both cases, the hub supplier is assumed to ultimately be the port of Rotterdam—APM Terminals Rotterdam (the Netherlands) and the hub customer is assumed to be the port of Shanghai—Yangshan Deep-water Port Phases 1/2 or 3/4 (People's Republic of China) enabling using the intermodal rail/road services for transporting containers to/from the Wusongkou, Waigaoqiao, and Yangshan deep-sea terminal group. In the west-east direction, the dedicated railway line to/from the port of Rotterdam is BetuweLine continuing to Germany, Poland, Belarus, and Russia. It meets the west-east line of the Nanjing railway network starting from the port of Shanghai and continuing to the West of China and further to Kazakhstan and Russia. Passing through different countries at two continents, the railway infrastructure and signaling systems can accommodate the intermodal trains

differently. In the European countries and China the normal gauge of 1435 mm and in Ukraine (or Belarus), Russia, and Kazakhstan the wide gauge of 1520 mm is used. The intermodal trains are of the block type having fixed composition implying no shunting and only technical stops and transshipment at the borders. The tractions system depending on the country is exclusively or mixed 3 kV DC, 25 kV AC50Hz, or diesel. The latter relates 850 km in Kazakhstan and 2000 km in China of non-electrified line, requesting use of either pure diesel or hybrid diesel-electric locomotives. Signaling system is ERTMS (West European countries, Poland), automatic block (Ukraine or Belarus, Russia, Kazakhstan), or lateral electric (China). The maximum permitted train length/axle load again depends on the country 650 m/22.5 t (Western Europe), 750 m/22.5 t (Poland), 850 m/13/23 t (Kazakhstan, China), 1200 m/- (Ukraine or Belarus), and 1300 m/23.5 t (Russia). The maximum speed of freight trains varies from 90 to 100 km/h. Despite the inherent heterogeneity of the corridor's infrastructure, traction and signaling system, the block trains of the same composition (capacity) are supposed to operate during the specified period of time. In addition, collection and distribution of freight shipments (TEUs) at the origin and destination hub, respectively, of the given supply chain are supposed to be carried out by road trucks (Bureika et al., 2016).

The container ships of the same capacity are used in the given deep-sea corridor serving the corresponding supply chain. They follow deep-sea route passing through China South Sea, Indian Ocean, Red Sea, Suez Channel, Mediterranean Sea, The Strait of Gibraltar, and Atlantic Ocean (North Sea), as shown on Figure 6. The route is without constraints on the ship size/capacity. The ships can operate there at different (assumed to be constant along the entire route) speeds of about 20, 15, and/or 10 kts, which is usually called "slow" and "super slow steaming" operating regime. The container terminals at its both ends in both above-mentioned ports are also without constraints on the ship size/capacity, thus enabling handling the largest container ships including the Triple E Maersk (18000 TEU). The collection and distribution of freight shipments (TEUs) at the above-mentioned deep-sea terminals of both ports is supposed to be carried out by rail, road, and/or inland waterways (barge), and feeder (including short-sea) vessel transport mode (Zhang et al. 2009). Figure 6 shows the simplified spatial scheme of both corridors.

4.1.2. Demand and supply characteristics of the chain served by particular corridors

The input data are collected and estimated from the chain's cases themselves and other relevant sources. The "what-if" operating scenario specifies characteristics of the freight transport demand and of supply by both corridors during a period of time. These are given for both corridors in Tables 1 and 2. Table 1 gives the input data for the chain served by intermodal rail/road freight transport corridor.

Table 2 gives the input data for the supply chain served by deep-sea freight transport corridor.

²Currently, this is one of the world's busiest chains (sea trading routes). It is included in the WCI (World Container Index) together with the remaining 10 most voluminous global container chains (sea trading routes) shares about 35% of their total volumes (TEUs) (<http://www.worldcontainerindex.com/>).

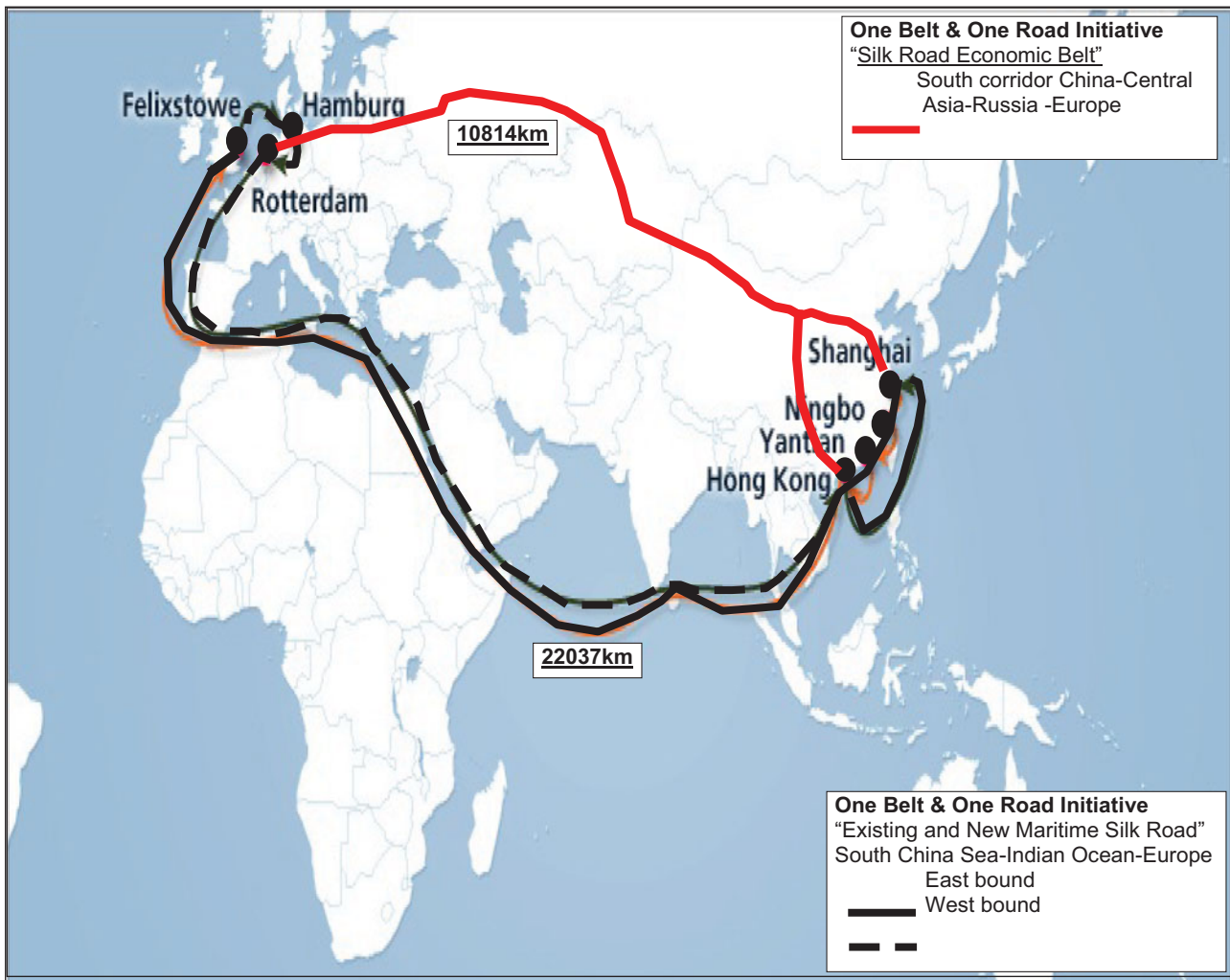


Figure 6. Supply chain geography: Rotterdam-Shanghai intermodal rail/road and deep-sea shipping route (Janić, 2016; <http://www.ship.gr/news6/hanjin28.htm>).
 (a) Average total unit cost (€/ton-km). (b) Average total cost (€/TEU).

Table 1. Input data for intermodal rail/road "Silk Road Economic Belt" corridor initiative (Bureika et al., 2016; DB Schenker, 2015; European Commission, 2012; Eurasian Development Bank, 2009; Janic, 2008; US Chamber of Commerce, 2006; Zhao, 2016).

Input variable	Notation/unit	Value
• Duration of the chain's production/consumption cycle	τ [year(s)]	1
• Number of containers per chain's production/consumption cycle	Q_{ij} (TEU/year)	45,000
• Train capacity	q_{ij} (TEU/Train)	144
• Train load factor	λ_{ij} (-)	0.80
• Time between the scheduled train departures between hubs	h_{ij} (day)	1
• Collection rate of containers at the hub supplier terminal	θ_i (TEU/h)	6
• Proportion of used collection rate of containers at the hub supplier port	r_i	1.0
• Distribution rate of containers at the hub customer port	θ_j (TEU/h)	6
• Proportion of used distribution rate of containers at the hub customer terminal	r_j	1.0
• Loading rate of containers at the hub supplier terminal	μ_i (TEU/h)	30 (1 crane)
• Proportion of used loading rate of containers at the hub supplier terminal	p_{ii}	1.0
• Unloading rate of containers at the hub customer terminal	μ_j (TEU/h)	30(1 crane)
• Proportion of used unloading rate of containers at the hub customer port	p_j	1.0
• Time between collecting and beginning of loading containers at the hub supplier terminal	Δ_i (day)	1
• Time between unloading and beginning distributing containers at the hub consumer terminal	Δ_j (day)	1
• Operating distance between the hub terminals	d_{ij} (km)	10814
• Average commercial/door-to-door train speed	v_{ij} (km/h)	26.0/20.5
• Average delay per realized transport service	D_{ij} (days)	0.0
• Inventory cost at the hub supplier and customer terminal	$\alpha_p \alpha_f$ (€/TEU-day) ^a	135; 135
• Container cost of time in transportation	α_{ij} (€/TEU-h)a	1.6
• Transport (train + pre/end road haulage)+handling cost at hub supplier and hub customer terminal	c_{ij} (€/t-km)a	0.657
• Average train + pre/end road haulage energy/fuel consumption	$f_{c/ij}$ (Wh/t-km)	26.6
• Average emission rate of GHGs [Green House Gas(es)] of train + pre/end road haulage	e_{ij} (gCO _{2e} /t-km)	12.8
• Risk of accident of container train	P_{ij} (probability of 1 event/year)	8.876×10^{-4}

^aAdjusted for change of value of € for period 2008–2016 (factor: 1.09). (<https://www.statbureau.org/en/eurozone/inflation>).

Table 2. Input data for deep-sea “Existing and New Maritime Silk Road” corridor initiative (Janic, 2016).

Input variable	Notation/unit	Value
• Duration of the chain’s production/consumption cycle	τ [year(s)]	1
• Number of containers per chain’s production/consumption cycle	Q_{ij} (TEU/year)	45,000
• Container ship capacity	q_{ij} (TEU/ship)	4000
• Container ship load factor	λ_{ij} (–)	0.80
• Time between the scheduled departures between hubs	h_{ij} (day)	26
• Collection rate of containers at the hub supplier port	θ_i (TEU/day)	500
• Proportion of used collection rate of containers at the hub supplier port	r_i	1.0
• Distribution rate of containers at the hub customer port	θ_j (TEU/day)	500
• Proportion of used distribution rate of containers at the hub customer port	r_j	1.0
• Loading rate of containers at the hub supplier port	μ_i (TEU/h)	92 (3 cranes)
• Proportion of used loading rate of containers at the hub supplier port	p_{i1}	1.0
• Unloading rate of containers at the hub customer port	μ_j (TEU/h)	92 (3 cranes)
• Proportion of used unloading rate of containers at the hub customer port	p_j	1.0
• Time between collecting and loading containers at the hub supplier port beginning	Δ_i (day)	1
• Time between unloading and distributing containers at the hub consumer port beginning	Δ_j (day)	1
• Operating distance between the hub ports	d_{ij} (nm/km)	11,899a/22,037
• Average operating speed of container ship	v_{ij} (kt/km/h)	20/37 (SS); 15/28 (SSS)
• Average delay per realized transport service	D_{ij} (days)	0.0
• Container inventory costs at the hub ports	$\alpha_p \alpha_j$ (€/TEU-day)	135; 135
• Container costs of time in transportation	α_{ij} (€/TEU-day)	2.24
• Container handling costs at the hub supplier port	c_i (€/TEU)	202
• Container handling costs at the hub customer port	c_j (€/TEU)	63
• Container ship operating costs	c_{ij} (€/TEU-km)/ v_{ij} (kts)	5.82/37; 3.23/28
• Average fuel consumption of container ship	$f_{c/ij}$ (ton/day)/ v_{ij} (kt)	150a/20; 68a/15
• Average emission rate of GHGs [Green House Gas(es)] of container ship	e_{ij} (tonCO _{2e} /day)/ v_{ij} (kt)	477/20; 216/15
• Risk of accident of container ship	P_{ij} (probability of 1 event/year)	35/1547

SS: slow steaming; SSS: super slow steaming.

^a<http://ports.com/sea-route/port-of-shanghai,china/port-of-rotterdam,netherlands/>

^bChurchill and Johnson, 2012.

The way of estimating inputs in Tables 1 and 2 is described as follows:

The number of containers (TEUs) per the chain’s production/consumption cycle of one year is determined by assuming that either corridor should serve 100% of it, i.e. exclusively. Each TEU is assumed to be of the constant gross weight. The capacity and utilization of Panamax ship require one monthly service to serve given volume of demand. The train capacity and its utilization require a daily service. This implies that one ship service is equivalent to 28 train services.

The rates of collection and distribution of freight shipments (TEUs) to be transported by train set up respecting the requirements for collecting and loading and then unloading and distributing them, respectively, during the period of 1 day (24 h). It is assumed that each train is loaded by single crane at both ends of the chain with the rate of 30 TEU/h. This implies that each train is loaded/unloaded in time of: 115 TEU/train: 30TEU/h = 3.75 h ~4.0 h. Consequently, the collection/distribution rate is assumed to be: 115: (24–4)=5.75 TEU/h ~6 TEU/h (Janić, 2014).

The loading and unloading rates of containers at both ports are set up based on the empirical evidence provided by both port terminals. In general, at both ends of the route Panamax ships are typically loaded/unloaded by three cranes simultaneously, over the period of 24 h/day (Mongelluzzo, 2013; SCG, 2013; Zhang et al., 2009).

For both corridors, the inventory costs of containers during collection and loading at the hub supplier and unloading and distribution at the hub customer are based on the average retail value of goods in containers and typical share of the inventory costs (25%) in that value (REM Associates, 2014).

The cost/value of time of freight shipments during being carried out by train are estimated based on the “value of each train” as follows: 13,026,000 €/train: 115 TEU/train = 113,270 €/TEU: 365 days/year = 310.3 €/TEU-day-0.12 (discount rate) = 37.2 €/TEU-day (DB Schenker, 2015).

The cost/value of time of freight shipments during being carried out by ship are estimated based on the value of trade between as follows: 525 billion€/0.30 (share of containerized goods): 23.1 million TEU (2015) = 6818 €/TEU: 365 days-0.12

(discount rate) = 2.24 €/TEU-day (European Commission, 2016; UN, 2007; United Nations Conference on Trade and Development, 2016; The Swedish National Road and Transport Research Institute (VTI), 2013).

The handling cost at both rail/road terminals

The transport cost by intermodal trains of the above-mentioned characteristics are estimated depending on the door-to-door delivery distance, which also included the cost of pre- and end-haulage by road and transshipment at both hub supplier and hub customer terminal as follows: $c(d) = 253.25 \cdot d^{-0.641}$ (Janić, 2008; <http://statbureau.org/en/eurozone>).

The handling costs of containers at both port terminals are based on empirical evidence (EC, 2009). The costs of container ships operating on high seas are estimated in light of 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; Davidson, 2014; Stopford 2003).

The energy consumption and related emissions of GHGs (CO₂) of freight trains is estimated as an average of using the electric and diesel traction along the line as follows:

- Europe: Distance: 1490 km; Speed: 100 km/h; Electrified 100%; Energy consumption: 25.2 Wh/t-km; Emission: 6.30 gCO₂/t-km (European Environmental Agency, 2015; Janic, 2008)
- Russia, Belarus or Ukraine, Kazakhstan: Distance: 4899 km; Electrified: 4049 km; Speed: 90 km/h; Energy consumption: 23.14 Wh/t-km; Emissions: 11.9 gCO₂/t-km; Non-electrified:

850 km; Speed: 90 km/h; Fuel consumption: 340 kg/h \equiv 3.8 g/t-km or 3.8 g/t-km · 13.333 Wh/g = 50.4 Wh/t-km (Russian M62 locomotive); Emissions: 0.0504 kWh/t-km · 513.18 gCO₂/kWh = 26.0 gCO₂/t-km. Average energy consumption: (4049/4899) · 23.4 + (850/4899) · 50.4 Wh/t-km = 28.08 Wh/t-km; Average emissions: (4049/4899) · 11.9 + (850/4899) · 26.0 = 14.3 gCO₂/t-km (Bureika et al, 2016, Eurasian Development Bank, 2009; Janić, 2008; US Chamber of Commerce, 2006).

- China: Distance: 4425 km; Electrified: 2425 km; Non-electrified: 2000 km; Operating speed: $v = 90$ km/h; Average energy consumption: (2425/4425) · 10.5 Wh/t-km + (2000/2425) · 32.8 = 32.8 Wh/t-km; Emissions: (2425/4425) · 10.4 + (2000/2425) · 9.35 = 13.4 gCO₂/t-km (Institute For Energy and Environmental Research Use, 2008).

The fuel consumption of container ships is estimated in terms of quantity used per day while operating on high seas at the given speed. The corresponding emissions of CO₂ are calculated using the emission rate of: $e_k = 3.18$ gCO₂/g of fuel [No. 6 Diesel or HFO (Heavy Fuel Oil)]. The fuel consumption and related emissions of CO₂ during the ships' time at berth in the ports are not taken into account (AECOM/URS, 2012; <http://www.scdigest.com/ontarget/13-09-12-1.php?cid=7401>).

Risk of incidents/accidents:

Train/Truck: The risk of train incidents/accidents is estimated as an average based the number of accidents/incidents of freight trains operating in the countries along the corridor (period: 1999–2014) (ERA, 2014; <https://en.wikipedia.org/>

Table 3. Assessed performance indicators of the given supply chains.

Indicator	Corridor	
	Intermodal rail/road	Deep-sea
Chain's production/consumption cycle (TEU/year)	45,000	45,000
Operational performances		
• Transport service frequency (dep/year)	390	14
• Vehicle turnaround time (cycle) (days/veh)	35.4	97.7
• Vehicle fleet size (veh-trains, vessels)	4	4
• Container fleet size (TEU-LU)	4364	12,045
• (Technical) productivity (TEU-km/h ²)	130.71	96.59
Economic performances		
• Inventory + in-transit time cost (€/year)	35,720,880	50,670,998 ^a 49,869,540 ^b
• Handling and transport costs (€/year)	31,920,330	38,884,216 ^a 57,458,380 ^b
• Total (inventory + handling + transport) costs (€/year)	67,641,210	89,555,214 ^a 107,327,920 ^b
• Average total unit cost (€/ton-km)	1.39	0.90 ^a 1.08 ^b
• Average total cost (€/TEU)	1503	1983 ^a 2380 ^b
Environmental and social performances		
• Energy (fuel) consumption (kWh/year)	129,443,500	349,624,938 ^a 578,423,657 ^b
• Energy (fuel) consumption (kWh/t-km) ^c	0.0266	0.0353 ^a 0.0583 ^b
• GHG emissions (Tons/year)	60289	99,943 ^a 165,481 ^b
• GHG emissions (gCO ₂ /t-km)	12.8	10.1 ^a 16.7 ^b
• Land use	n.a.	n.a.
• Noise	n.a.	n.a.
• Congestion	Included	Included
• Risk of incidents/accidents ^d	8.876×10^{-4}	35/1547

^aSpeed: 15 kts.

^bSpeed: 20 kts (Bunker C fuel: 40 MJ/kg).

^c1TEU \equiv 10 ton.

^dFor rail it is the risk for an event to happen per day.

[wiki/List_of_rail_accidents_by_country](#)). The risk of accidents/incidents of road trucks is not taken into account.

Ship: The risk of incidents/accidents causing a loss of one container ship per period of time (1 year) is estimated as the product of two probabilities: (i) the probability of losing a container ship in a freight ship accident; and (ii) the probability of such an accident occurring within the given chain/route (region). The former 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), while the latter probability is estimated as the quotient of the number of ships lost in accidents that occurred 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 Global Corporate & Speciality, 2013; United Nations Conference on Trade and Development, 2016).

In addition, it should be mentioned that due to the specificities of given cases, the inputs for estimating indicators of environmental performances related to land use and that of social performances related to noise and congestion, as presented in the above-mentioned corresponding models, was missing for too many data inputs (and therefore not further considered). Another main important reason is also their incompatibility for comparison for the respective corridors. However, this does not compromise the quality and generality of application of the proposed models.

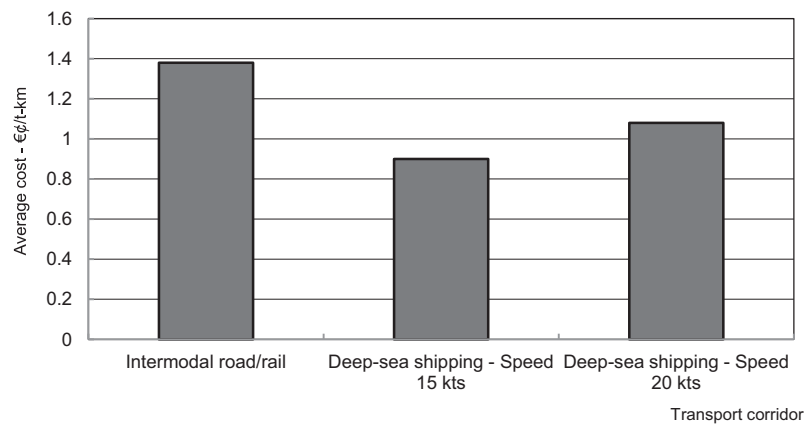
4.2. Results

Some results of assessing indicators of particular performances of the given supply chain are given in Table 3 and Figures 7(a,b) and 8(a,b).

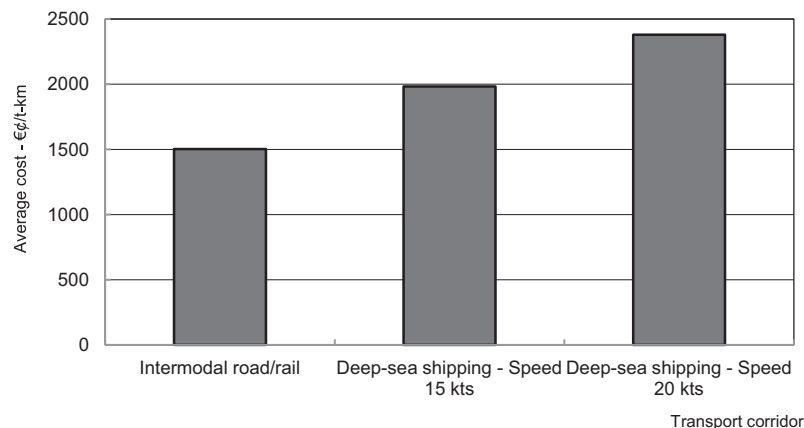
Operational: We assumed two chains for both rail/road and sea of 45,000 TEU on a yearly basis. For rail this would mean an important chain while for sea transport it would mean a relatively small flow. The operational characteristics for rail show higher frequencies and larger vehicle fleet sizes (train) as compared to deep sea. Given the larger vessel size it is logical that the number of needed Load Units (LU) is larger for deep-sea as compared to rail transport. In the technical productivity the difference in distance (factor two for deep-sea) can be observed in total TEU/kms per year and per LU.

Economic performance: The economic performances of both options show that the inventory cost are much larger than the transport and handling cost. It should however, be taken into consideration that the transport and handling cost are out of pocket costs and the inventory cost are not. In the economic performance the overall costs are lower for rail, the costs per ton-km are higher for rail but per LU again the costs are lower for rail.

Environmental and social performance: The overall performance of rail shows that the environmental and social performance of rail transport is considerably better than that of sea transport. In terms of ton-km performance the results

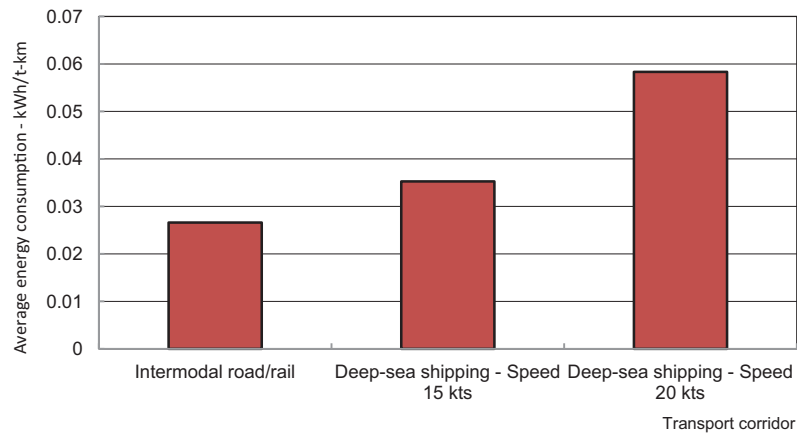


(a) Average total unit cost (€/ton-km)

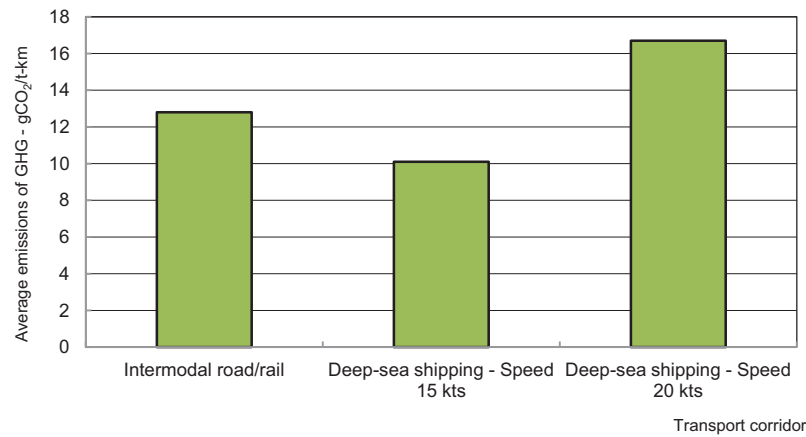


(b) Average total cost (€/TEU)

Figure 7. Economic performances. (a) Energy consumption. (b) Emissions of GHG (CO₂).



(a) Energy consumption

(b) Emissions of GHG (CO₂)**Figure 8.** Environmental performances.

for rail and sea are somewhat mixed. Disadvantages of rail are more noise nuisance and more land use. Although it could be questioned if these are really performances or rather characteristics of the rail transport mode.

5. Conclusions and discussion

The article investigated if the supply chains served by the long-distance rail/road intermodal corridor could be equally if not more attractive than the supply chains served by the current dominant deep-sea corridor. This is carried out by an analysis, modeling, and estimating operational, economic, and environmental/social performances of both types of corridors operating as independent alternatives given their infrastructural and technological/technical capabilities. The infrastructure capabilities have shown that both chain and route length(s) have been considerably shorter at the rail/road than at the deep-sea corridor alternative. Furthermore, the accessibility of the deep-sea transport services has been relatively good though for the large container ports at the begin and end of the given corridor. For the rail/road corridor, this has been more evenly spread (begin, intermediate, and end terminals). The area coverage and infrastructure density has shown to be higher for the rail/road alternative than its deep-sea counterpart. The technical/technological capabilities of the deep-sea alternative have reflected much

higher size and utilization of capacity of the vehicles (ships) and corresponding terminal facilities and equipment compared to that of the rail/road alternative. The operational performances have shown that the transport service frequencies of rail/road alternative have been potentially higher than that of the corresponding deep-sea services given their lower volumes of freight carried per frequency. However, the vehicle fleet size and the technical productivity of deep-sea have shown to be superior given its much larger scale. The economic performances of the respective corridors have shown that on the one hand, the inventory costs of the rail/road alternative would be lower given its lower transported volumes per service frequency and shorter transport time. On the other hand, they might be higher given their higher average transported values. However, the total handling and transport costs have shown to be considerably higher for the deep-sea alternative. While the average unit costs have been lower, mainly due to spreading over the much larger freight volumes. As far as the environmental and social performances are concerned, the rail/road alternative has shown to be much more environmentally friendly than its deep-sea shipping counterpart mainly due to using electricity for propulsion as compared to crude oil used by deep-sea shipping. In addition, the rail/road alternative has performed better regarding the rest of indicators of performances except noise.

Overall, the performances of supply chains served by the intermodal rail/road corridor(s) have shown to be better but only under the assumption that the necessary conditions are fulfilled to enable fair comparison with those served by the deep-sea shipping alternative. This implies that if these conditions are fulfilled, the rail/road alternative would be able to act as a reasonably serious competitive alternative to the deep-sea transport alternative in the given context. However, in order to realize this opportunity, rather large investments in the rail/road infrastructure are required in order to appropriately connect China with Europe. In Europe, history has shown that it has been quite complex to improve the long-distance rail transport. In China, however, the substantive investments programs supported by corresponding national policy are supposed to back the OBOR initiative. Consequently, the successful changes in the modal shift in favor of rail/road freight transport alternative could lead to both cost reductions and efficiency improvements—exactly what the intermodal rail/road freight corridor from China to Europe would try to achieve by serving freight volumes of certain goods categories.

Further research could be focused on the issues related to the competitiveness of the rail/road alternative to its deep-sea counterpart in the given context respecting:

- a. Different freight/goods categories;
- b. Alternative routes;
- c. The environmental and social performances in more details; and
- d. Capacity of the corridors particularly that of the rail/road alternative.

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