Lead-time-based freight routing in multi-modal networks considering the Physical Internet

Shahedi, Alireza; Gallo, Federico; Saeednia, Mahnam; Sacco, Nicola

DOI
10.59490/jscms.2023.7183

Publication date
2023

Document Version
Final published version

Published in
Journal of Supply Chain Management Science

Citation (APA)
Shahedi, A., Gallo, F., Saeednia, M., & Sacco, N. (2023). Lead-time-based freight routing in multi-modal networks considering the Physical Internet. *Journal of Supply Chain Management Science*, *4*(3-4), 61-80. https://doi.org/10.59490/jscms.2023.7183

Journal of Supply Chain Management Science

https://journals.open.tudelft.nl/jscms

http://dx.doi.org/10.18757/jscms.2023.7183

Lead-time-based freight routing in multi-modal networks considering the Physical Internet

Alireza Shahedi [a], Federico Gallo [a*], Mahnam Saeednia [b], and Nicola Sacco [a]

[a] *Department of Mechanical, Energy, Management and Transport Engineering, University of Genoa, Genoa, Italy*

[b] *Department of Transport and Planning, Delft University of Technology, Delft, Netherlands*

Article history: received 30-09-2023, accepted 14-12-2023, published 29-12-2023

Abstract – This paper addresses the problem of optimizing the transport of goods in the Physical Internet (PI) framework in a multi-modal setting using a multi-objective mixed-integer linear programming (MILP) approach. The model is specifically designed to meet the requirements related to modular shipments and PI-hubs, and in particular, determines the allocation of modular shipments to each transport mode in an intermodal setting. In doing so, parallel direct connection via road, the delivery times and the transportation costs are minimized. The model is applied to a numerical case study, to test its effectiveness to enhance freight transport efficiency within the PI framework, by exploiting, in particular, all the capacities of the available vehicles. In addition, a sensitivity analysis is conducted on some model parameters, to test its reaction to changes in the supply system and in the objective priorities. Results show that all the shipments are effectively transported between the origin and the destination terminals, they are divided into modules when necessary, and the selected transport modes, allocation strategy, and delivery times vary accordingly to the objective priorities.

Keywords: Freight transport; physical internet; optimization

1. Introduction

The Physical Internet (PI) is characterized as "a worldwide logistics system that is open in nature and relies on the interconnection of physical, digital, and operational aspects through encapsulation, interfaces, and protocols" (Meller et al., 2012). The shipments are transported within this framework using standardized containers, similar to how data packets are transmitted in the Digital Internet. According to the Physical Internet concepts in logistics, there are three main elements: the PI-containers, the PI-movers (PI-vehicles, PI-conveyors, PI-carriers), and the PI-nodes (PI-hubs, PI-sorters, PI-transit, etc.) (Montreuil et al., 2010). Generally, the PI-hubs' goal is to transfer shipments (i.e., the PI-containers) from the incoming vehicles (i.e., the PI-movers) to the outgoing ones.

Ballot et al. (2012a) presented a pioneering road-rail PI-hub designed specifically for the complicated task of intermodal container transfers, showcasing its adaptability in facilitating seamless transitions between trucks and trains, as well as inter-train exchanges. The road-rail PI-hub encounters three transfer instances:

- Road-rail transfer: a precise process is required to shift containers from trucks to train wagons, orchestrated through precise road-rail sorting mechanisms.
- Rail-rail transfer: the hub must efficiently manage transfers between different train wagons, demanding specialized rail-rail sorting systems for optimal operations.
- Rail-road transfer: focuses on transferring containers from wagons to outgoing, using rail-road PI-sorters.

*Corresponding author. Email address: federico.gallo@unige.it

The aim of this paper is to apply the principles of the Physical Internet to design an efficient and flexible logistics network that can handle various transshipment scenarios in terms of size and modes considering all three transshipment types mentioned above. This includes exploring the roles of key elements within the PI and leveraging standardized containers for more efficient transportation processes. A generic freight transportation network usually comprises various elements: suppliers, distribution centers, terminals, PI-hubs, and customers. However, this study focuses on the section between the origin and the destination terminals, according to the network described in the following.

In more detail, the addressed network offers two different possibilities to deliver shipments, that is, a direct connection operated by trucks and a combination of rail-road or rail-rail modes, enabled by the “road-rail PI-hub” The task involves assigning modules of each shipment to trains or trucks based on their destinations, enabling the possibility of travelling along different paths. In doing so, three objectives are minimized: firstly, the use of direct trucks, which, bypassing the PI-hubs, connect the origin terminals to the destination ones; secondly, the total delivery time of each shipment in reaching the destination terminals; lastly, the total transportation cost. The choice of minimizing the use of direct trucks is motivated by the aim of reducing emissions that are usually associated with such a mode. Optimizing shipment routing, ensures streamlining the transportation process and reduction of overall travel distance resulting in an efficient shipment delivery. These objectives pose a challenge, as minimizing costs often necessitates using efficient hub-based systems, whereas minimizing the delivery time results in increasing the direct truck usage. Balancing these goals will require innovative solutions to optimize logistics performance while minimizing direct truck usage and contributes to the practical application of the Physical Internet concept. Another important requirement for such applications addressed in this paper, is consideration of modular shipments and ensuring that all modules arrive at their destination within the required time.

The paper is organized as follows: Section 2 discusses the existing literature related to this work; Section 3 describes the considered problem and the main assumptions; in Section 4 the proposed optimization model is explained; Section 5 presents the results of the application of the proposed model to a numerical case study; finally, some concluding remarks and future research directions are mentioned in Section 6

2. Literature review

The Physical Internet represents an innovative approach to the global logistics network organization, revolutionizing the existing logistics system. Its primary goal is to enhance the economic, environmental, and societal efficiency and sustainability of worldwide transportation, storage, realization, supply, and utilization of physical goods which was initially introduced and presented by Montreuil (2011). The term “Physical Internet” mirrors the Internet's functioning, using its digital metaphor to innovate logistics in the physical realm. Like the vast neural network of the Digital Internet effortlessly transfers data, the Physical Internet aims for goods to move seamlessly without user intervention across diverse networks. Ballot et al. (2014) described the core of the Physical Internet as a connected and resilient logistics network aimed at enhancing the transportation of diverse goods. It focuses on meeting customer specifications, improving economic models, and minimizing environmental impact through various measures like routing protocols, traceability standards, and innovative trade configurations. This concept shapes the Physical Internet as a globally linked logistics system integrating physical, digital, operational, business, and legal aspects.

Such a paper provides a comprehensive overview of the fundamental principles underlying the PI, including the application of the Internet metaphor. It introduces the key components of the PI, namely PI containers and PI hubs, from a conceptual standpoint, and explores the potential economic, environmental, and social benefits associated with its implementation. Furthermore, prior research has been conducted on the design of PI hubs, which vary depending on intermodal requirements. Notably, three-part PI hub proof-of-concept designs have been developed for unimodal road, railroad, and road-based transit centers, demonstrating the practical implementation of PI principles within specific transportation contexts (Venkatadri et al., 2016; Montreuil et al., 2013).

Ballot et al. (2012b) argued in favor of decentralized and distributed routing solutions for the Physical Internet (PI) as a preferable alternative to classical network design methods when addressing flow assignment problems, primarily due to the expansive scale of the PI concept. Recognizing the unique challenges posed by the PI's large-scale nature, the authors propose an evolutionist approach to tackle the problem of open hub network design within the PI framework.

Since 2014, the concept of PI has emerged as a strategy to enhance logistics efficiency by establishing synchronized connections among logistics networks (Sarraj et al., 2014). During that year, Lin et al. (2014) started a novel work for PI by proposing the standardization of packaging and containers, aiming for reliable product handling within the network to increase efficiency. Between 2015 and 2016, studies continued to focus on PI-container design (Sallez et al., 2016), alongside a significant rise in research exploring logistics operations within the framework of PI. These investigations explored transportation and inventory problems (Pan et al., 2015) and resource allocation (Walha et al., 2016).

Between 2017 and 2018, scholars began broadening the scope of the PI concept to encompass the manufacturing shop floor (Onal et al., 2018; Zhong et al., 2017) and urban logistics (Ben Mohamed et al., 2017; Fazili et al., 2017; Sun et al., 2018).

Regarding the role of PI in logistics, Lin et al. (2014) introduced a mathematical model along with a decomposition algorithm for the maximizing space utilization problem for packing a given set of products. The objective is to optimize the selection of the number and size of modular containers. Through a case study, the authors demonstrate how the implementation of standardized containers, which is one of the key principles of the Physical Internet (PI), leads to enhanced utilization of vehicle space.

To comprehend the expenses associated with PI, a comprehensive assessment of the network's flow mechanisms becomes imperative. Fazili et al. (2017) conducted a comparative analysis of the conventional PI, and hybrid logistics systems within a road network. The study introduced key performance indicators (KPIs) including the number of container packing and unpacking occurrences, as well as the cumulative driving time. The evaluation was carried out by employing three optimization models that were sequentially executed using generated data. Ballot et al. (2011) focused on examining the structure of both traditional PI networks within a supply chain scenario involving a single warehouse that supplies multiple regional distribution centers. Utilizing the continuous approximation method, the researchers derive analytical terms to assess the material flow. A comparative analysis of the traditional and PI networks is subsequently conducted, considering three primary criteria: 1) flow travel; 2) transportation cost; and 3) total inventory in the supply chain. The findings consistently indicate that the project implementation approach outperforms the traditional logistics network across all three criteria. Based on the results of the analysis, it can be concluded that the PI approach surpasses the traditional logistics network in terms of each criterion. Chargui et al. (2019) proposed a Rail–Road cross-docking PI-hubs, aiming to minimize total costs by optimizing truck schedules. They formulated the problem as a Multi-Objective Mixed-Integer Programming model (MO-MIP) and solved it using two hybrid multi-objective meta-heuristics: Multi-Objective Variable Neighbourhood Search combined with Simulated Annealing (MO-VNSSA) and Tabu Search (MO-VNSTS). They also presented another study which delves into how Physical Internet (PI) transforms cross-dock design and optimization, exploring unique features and challenges. It compared PI-cross-docks with traditional designs and outlined optimization challenges under the PI paradigm. Finally, it presented a preliminary study on a new PI-based problem (Chargui et al., 2022).

2.1 Routing containers in multi-modal networks

According to Crainic and Kim (2007), intermodal transportation can be defined as the process of transporting individuals or cargo from their starting point to their final destination using a series of at least two transportation modes. The transfer from one mode to another occurs at a terminal or, in PI framework, in the PI-hubs which, in the considered Physical Internet paradigm represent the nodes where modules can be delivered and dispatched by different transportation modes, ideally in a seamless way.

The intermodal transportation problem encompasses three main areas of research: terminal location, transportation route selection, and transportation mode choice.

Some investigations have been done regarding the intermodal transport route selection. Boussedjra et al. (2004) conducted a study on a model that aims to determine the shortest path between origins and destinations within intermodal transportation networks. The authors explored the use of a multi-label graph approach for this purpose. Zhang et al. (2006) proposed the problem of finding the optimal transportation path in an intermodal transportation network. The authors implemented the Dijkstra algorithm as a solution methodology for determining the most efficient route. Sawadogo et al. (2012) introduced a novel multi-objective model that aims to minimize both the environmental and social impacts within intermodal transportation networks to find the shortest path. Zhang et al. (2015) proposed a bi-objective model for selecting intermodal transportation routes, which takes into account two key factors: reliability and cost. By explicitly considering both these factors, the authors aimed to provide a comprehensive framework for optimizing route selection in intermodal transportation.

Regarding the transportation mode selection in the context of intermodal transport problems, Zhang et al. (2011) presented an optimization approach to minimize the costs for logistics and carbon emissions in a terminal network to select the best choice of transportation mode. Saeed (2013) conducted a study to evaluate and contrast the vertical and horizontal cooperation among freight forwarders. The research focuses on the analysis of three freight forwarders, also referred to as “players” which operate within two distinct modes of transportation. The findings indicated that the most effective form of collaboration is characterized by the establishment of a coalition between the large truck-operating company and the ship-operating company, referred to as vertical cooperation. Reis (2014) created an innovative agent-based model that simulates the transportation operations and behavioral responses of transport agents by incorporating mode choice variables that are commonly recognized as crucial in the mode selection process, namely price, transit time, reliability, and flexibility. The primary objective of using this model was to evaluate the performance of competing transport modes, specifically intermodal and road, across diverse demand scenarios. Qu et al. (2019) presented a mixed-integer linear programming method model for replanning hinterland freight transportation within the synchromodal framework. It offers a comprehensive solution that involves rerouting shipment flows, organizing transshipments at intermediate terminals, and adjusting related service schedules. Lemmens et al. (2019) introduced a decision-making guideline that incorporates simultaneous use and instantaneous switching of transport modes, whether used together or independently. It considers the current inventory and service needs of the shipper in real-time. The strategy initially decides the allocation of shipment volumes to various transport modes from the source. Following this, it evaluates whether mode switching at an intermediate terminal is necessary. They presented how their synchromodal transportation strategy can encourage a transition to environmentally friendly transport modes. Huang (2021) created a two-stage stochastic programming model considering uncertainties in transportation service capacity and travel times. The aim was to maximize the intermodal transportation operator’s anticipated profit by selecting the best order portfolio and planning intermodal routes. Briand et al. (2022) conducted a survey on dynamic routing protocol with payments for the Physical Internet. They proposed a protocol that reduces the prices and empty mileage by approximately 10% and 20% respectively. Their protocol exhibits enhanced routing resilience provided that nodes engage in accurate prediction. Dong et al. (2021) presented a framework developed for the PI network, building upon the foundation laid by DI, revealing that beyond addressing the basic problem of routing from A to B, the PI network faces a more intricate task of optimizing various logistics metrics such as cost, emissions, and time dynamically during shipment. Kaup et al. (2020) presented a research concept by introducing an artifact that views the PI-nodes as routers, facilitating the distribution and replication of real-time data among these nodes. This approach aims to enhance the efficiency of routing decisions. The real-time data originates from vehicles known as PI-transporters operating on the roads. Consequently, a secondary design was formulated wherein these PI-transporters perform the routing operation.

As it emerges from the literature analysed above, while intermodal freight transportation has been widely addressed, considering the PI concept applied to the optimization of a freight transportation network is still at its infancy. For this reason, this paper’s key contribution lies in creating an optimization model for freight delivery within a logistics network following the PI framework. Here, shipments are divided into modules that can be taken apart, sent using various transportation methods simultaneously, and later put back together at the destination terminal. This problem also addresses routing and timing issues with respect to the destination of the modules and their delivery time. Moreover, the possibility of direct transfer by trucks is included in the model to ensure the fulfilment of transportation demand, whereas consideration of minimizing the usage of the direct truck in the objective function ensures the priority of intermodal transport in transporting goods. This leads to the growth of the greenness index in our proposed network contributing to ecological sustainability.

3. The considered transport system

This section describes the considered PI-based freight transport system, to which the optimization problem described in section 4 is applied; it also presents the related modeling assumptions.

As regards the shipments, the basic idea of PI consists of the possibility of dividing a single shipment into a set of smaller modules, also addressed as PI-containers, which can be delivered with different transport modes and along different paths. Such a characteristic has the capability of exploiting the residual capacity of already existing services (i.e. already planned trains or truck trips) that cannot accommodate the entire volume of the shipment, namely V_s, but have enough space for part of it. The expected benefits consist of a better use of the transport mode capacities and of a potential reduction of circulating vehicles as it may happen if the already existing services can accommodate all the modules. Nevertheless, in this framework, a shipment can be considered delivered only when the last module reaches the destination.

An example of the PI modular containers is reported in Figure 1, where the complete shipment on the left (that can be thought of as a TEU) is divided into a set of seven smaller PI-containers that are delivered separately.

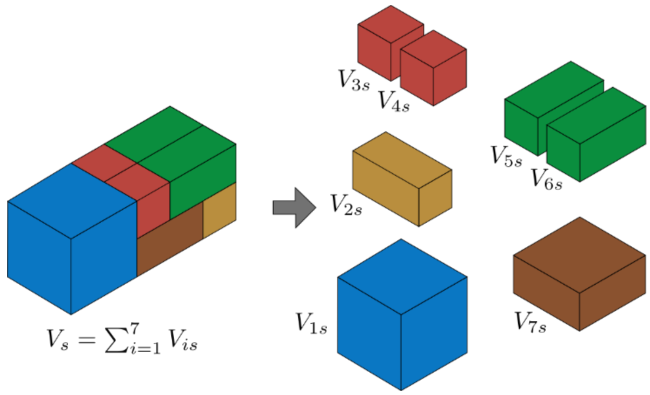

Figure 1. PI principle – any generic shipment s is divided into a set of modules that can be delivered separately. The total volume is conserved.

In this framework, freight delivery can be realized by means of the transportation network scheme reported in Figure 2, where the different nodes correspond to:

- Distribution centers, which represent the origins and the destinations of any different shipment, being directly linked to the suppliers and the customers. For the sake of simplicity, in the example network only one origin (yellow) and one destination (pink) are depicted;
- Terminals, which are directly connected with the distribution centers and the PI-hubs, represent the most general nodes of the network. In such nodes, shipments are disaggregated in modules or modules are aggregated into a single shipment. In addition, in such nodes, other operations, such as consolidation, custom operations, etc., can be performed. Note that, for each shipment, these nodes can be classified as origin (blue) and destination (green) terminals, although each of them can operate for different shipments, both as origin and destination;
- PI-hubs (light blue), which represent intermediate nodes where modules can switch from a transport mode to another. It is assumed that these nodes are dedicated only to the PI-network such that the relevant operation can be internally optimized for the PI logistic scheme. In this connection, PI-hubs are designed to accommodate the principles of the Physical Internet, for instance by implementing a fast mode switch, possibly in a fully automated environment, without the need of a significant storage capacity. These hubs exemplify the cutting-edge approach of integrating various aspects of the Physical Internet, including modularization, standardization, and intelligent routing, to streamline the movement of goods. In fact, PI-hubs are designed to enable a smooth transshipment of PI-containers between modes and are equipped with a PI-sorter and two manoeuvring zones located at the loading/unloading dock sections, facilitating efficient operations and transfers between different modes of transportation. The cross-docking process begins with the unloading of PI-containers from the wagons or incoming trucks, after which they are sorted based on their respective destinations and transported to the assigned outbound docks. Subsequently, the PI-containers are loaded onto the outgoing trains or trucks and are then transported to their respective destinations.

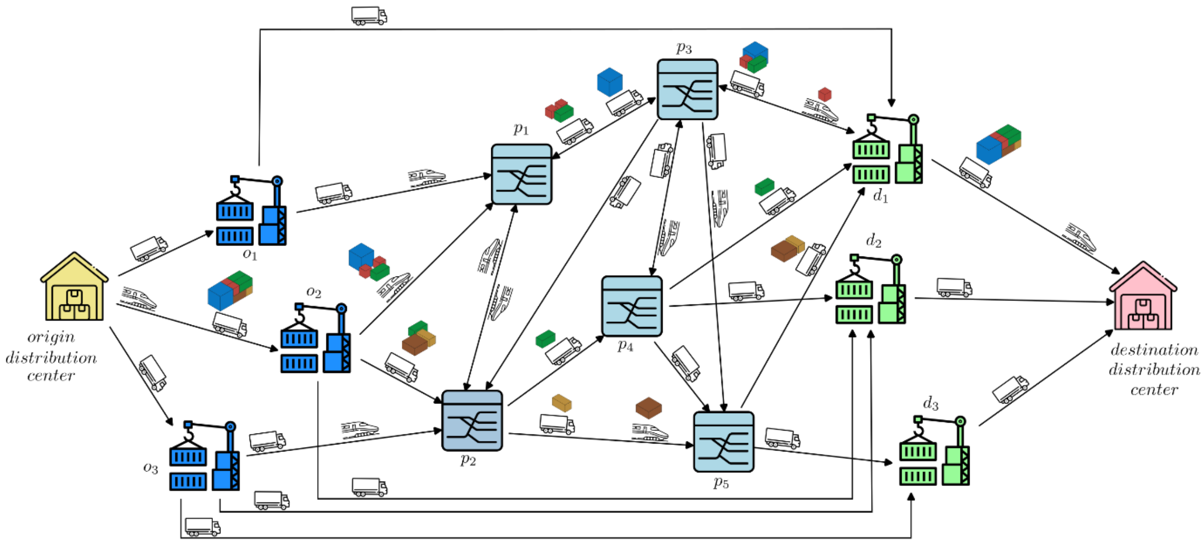

Figure 2. Scheme of the considered network and an example of shipment subdivision and routing where trucks and trains represent already planned connections. The generic shipment s in the example is assigned to the origin terminal o_2, where it is disaggregated into modules differently routed based on the residual capacity of the planned rail/road connections and aggregated at the destination terminal d_1.

From the modeling point of view, the network is represented as a directed graph, where nodes represent terminals and PI-hubs and links specify the connections among them. Each generic link is associated with a set of road or rail connections operated by planned trucks or trains each characterized by a given departure time and -capacity. In other words, the routing of modules in such a network can be thought of as the assignment of each to proper modes.

In such a scheme, for any generic shipment s, the following relations is assumed:

- origin terminals, hereafter gathered in the set $\mathcal{O}_s$, can have origin distribution centers as predecessors and PI-hubs or, only for the so-called dedicated truck connections, destination terminals, as successors;
- destination terminals, hereafter gathered in the set $\mathcal{D}_s$, can have destination distribution centers as successors and PI-hubs or, only for the so-called dedicated truck connections, destination terminals, as predecessors;
- PI-hubs can have terminals and other PI-hubs as predecessors and successors.

Summarizing, in such a logistic scheme, shipments are initially transported from the origin distribution center to one of the origin terminals, where they are disaggregated into modules, and then delivered according to the available services. Then, shipments are reaggregated in one of the destination terminals and then delivered to the distribution center.

In addition, the following assumptions are also considered:

- a single origin and destination distribution center are considered;
- PI-hubs and terminals are connected via road and rail;
- each PI-hub has a specific average operation time for the modules to transfer them from the incoming to outgoing sections;
- the travel times of the network links and the operation times are known and fixed.

4. Problem formulation

This section describes the mathematical model for the optimization of the freight transportation system introduced in section 3, which is formulated as a multi-objective mixed-integer linear programming (MO-MILP) model. The first objective is to minimize the number of trucks used for direct shipping in order to satisfy the economic and environmental aspects regarding the Green Deal (European Commission, 2023) and the European governments tendency. The second objective is to minimize the overall delivery time of the modules, which may be conflicting with the first objective, in case of higher transshipment time at the PI-hubs. Finally, the third objective minimizes the total cost of transportation in the network. The model considers several parameters such as train departure times, transshipment durations of each module, PI-hub operation times, travel time of each mode connecting the nodes, and capacities of trucks and trains. The problem notation is shown in Table 1.

Table 1. Problem notation.

Sets	
$\mathcal{O}_s$	Set of origin terminals of the shipment s
$\mathcal{D}_s$	Set of destination terminals of the shipment s
$\mathcal{P}$	Set of the PI-hubs
$\mathcal{N}$	Set of all the nodes, i.e., $\mathcal{N} = \mathcal{O}_s \cup \mathcal{D}_S \cup \mathcal{P}$
$\mathcal{S}$	Set of shipments
$\mathcal{I}_s$	Set of the modules corresponding to the generic shipment $s, \forall s \in \mathcal{S}$
$\mathcal{F}_j$	Set of generic input nodes of the node j. $\mathcal{F}_j$ gathers all the nodes k such that a link (k, j) exists
$\mathcal{B}_j$	Set of generic output nodes of the node j. $\mathcal{B}_j$ gathers all the nodes k such that a link (j, k) exists
$\mathcal{R}_{j,k}$	Set of trains connecting two generic nodes $j \in \mathcal{N}$ and $k \in \mathcal{N}$
$\mathcal{T}_{j,k}$	Set of trucks connecting two generic nodes $j \in \mathcal{O}_s$ and $k \in \mathcal{D}_S$
$\mathcal{C}_{j,k}$	Set of trucks connecting two generic nodes $j \in \mathcal{N}$ and $k \in \mathcal{N}$
Parameters	
V_{is}	The volume of module i of shipment s
$c^{jk\ell}$	The cost of using each of the transportation mode $\ell \in \mathcal{R}_{j,k} \cup \mathcal{C}_{j,k} \cup \mathcal{T}_{j,k}$ connecting the nodes $j \in \mathcal{N}$ and $k \in \mathcal{N}$, and 0 otherwise
$\Gamma^{jk\ell}$	Capacity of a generic transport mode $\ell \in \mathcal{R}_{j,k} \cup \mathcal{C}_{j,k} \cup \mathcal{T}_{j,k}$ connecting the nodes $j \in \mathcal{N}$ and $k \in \mathcal{N}$, and 0 otherwise
$t^{jk\ell}$	Travel time of the transport mode $\ell \in \mathcal{R}_{j,k} \cup \mathcal{C}_{j,k} \cup \mathcal{T}_{j,k}$ connecting the nodes $j \in \mathcal{N}$ and $k \in \mathcal{N}$, and 0 otherwise
tf_k	Travel time from the terminal $k \in \mathcal{D}$ to the destination distribution terminal
τ_p	Average operation time of the PI-hub $p \in \mathcal{P}$
$d^{jk\ell}$	Departure time of the transport mode $\ell \in \mathcal{R}_{j,k} \cup \mathcal{C}_{j,k} \cup \mathcal{T}_{j,k}$ connecting the nodes $j \in \mathcal{N}$ and $k \in \mathcal{N}$, and 0 otherwise
α, β, γ	Weighting coefficients in the objective function
θ_s	Priority associated with shipment s
a_{is}^k	Arrival time of module i of shipment s at node $k \in \mathcal{O}_s$
Decision variables	
$z_{is}^{jk\ell}$	1 if module i of the shipment s is assigned to direct truck $\ell \in \mathcal{T}_{j,k}$ from origin terminal j to destination terminal k, and 0 otherwise
$y_{is}^{jk\ell}$	1 if module i of the shipment s is assigned to train $\ell \in \mathcal{R}_{j,k}$ connecting the nodes $j \in \mathcal{N}$ and $k \in \mathcal{N}$, and 0 otherwise
$x_{is}^{jk\ell}$	1 if module i of the shipment s is assigned to truck $\ell \in \mathcal{C}_{j,k}$ connecting the nodes $j \in \mathcal{N}$ and $k \in \mathcal{N}$, and 0 otherwise
w_{is}^j	1 if the module i of the shipment s is assigned to the origin terminal $j \in \mathcal{O}_s$, and 0 otherwise
u_{is}^k	1 if the shipment s is assigned to the destination terminal $k \in \mathcal{D}_s$, and 0 otherwise
Other variables	
DT_s	Delivery time of shipment s to destination distribution center
DT_s	Delivery time of shipment s to destination distribution center
DT_s^k	Delivery time of shipment s to destination terminal $k \in \mathcal{D}_s$
ρ_{is}^k	Delivery time of module i of shipment s at the node $k \in \mathcal{P} \cup \mathcal{D}_s$
φ_{is}^k	Delivery time of module i of shipment s sent entirely by truck to destination terminal $k \in \mathcal{D}_s$

The problem is formalized as a multi-objective mathematical programming model aimed at minimizing the following terms:

$$J_1 = \sum_{s \in \mathcal{S}} \sum_{i \in \mathcal{I}_s} \sum_{j \in \mathcal{O}_s} \sum_{k \in \mathcal{D}_s} \sum_{\ell \in \mathcal{T}_{j,k}} z_{is}^{jk\ell} \tag{1}$$

which represent the overall usage of the direct trucks for transporting modules between the terminals,

$$J_2 = \sum_{k \in \mathcal{D}_s} \sum_{s \in \mathcal{S}} \theta_s \cdot DT_s^k \tag{2}$$

which represents the total delivery time of the shipments to the destination terminals, and

$$J_3 = \sum_{i \in \mathcal{I}_s} \sum_{s \in \mathcal{S}} \left(\sum_{j,k \in \mathcal{N}} \left(\sum_{\ell \in \mathcal{R}_{j,k}} c^{jk\ell} y_{is}^{jk\ell} + \sum_{\ell \in \mathcal{C}_{j,k}} c^{jk\ell} x_{is}^{jk\ell} \right) + \sum_{j \in \mathcal{O}_s} \sum_{k \in \mathcal{D}_s} \sum_{\ell \in \mathcal{T}_{j,k}} c^{jk\ell} z_{is}^{jk\ell} \right) \tag{3}$$

which represents the total cost of the trains and trucks for transporting shipments.

Therefore, the resulting problem consists of finding the values of the variables $x_{is}^{jk\ell}$, $y_{is}^{jk\ell}$, $z_{is}^{jk\ell}$, u_{is}^{j}, and w_{is}^{j} that minimize the overall cost function:

$$J = \alpha J_1 + \beta J_2 + \gamma J_3 \tag{4}$$

subject to:

$$DT_s^k \geq \varphi_{is}^k \qquad \forall i \in \mathcal{I}_s, s \in \mathcal{S}, k \in \mathcal{D}_s \tag{5}$$

$$DT_s^k \geq \rho_{is}^k \qquad \forall i \in \mathcal{I}_s, s \in \mathcal{S}, k \in \mathcal{D}_s \tag{6}$$

$$DT_s \geq DT_s^k + tf_k \qquad \forall s \in \mathcal{S}, k \in \mathcal{D}_s \tag{7}$$

$$a_{is}^j \leq d^{jk\ell} x_{is}^{jk\ell} + M\left(1 - x_{is}^{jk\ell}\right) \qquad \forall \ell \in \mathcal{C}_{j,k}, j \in \mathcal{O}_s, k \in \mathcal{P}, i \in \mathcal{I}_s, s \in \mathcal{S} \tag{8}$$

$$a_{is}^j \leq d^{jk\ell} y_{is}^{jk\ell} + M\left(1 - y_{is}^{jk\ell}\right) \qquad \forall \ell \in \mathcal{R}_{j,k}, j \in \mathcal{O}_s, k \in \mathcal{P}, i \in \mathcal{I}_s, s \in \mathcal{S} \tag{9}$$

$$a_{is}^j \leq d^{jk\ell} z_{is}^{jk\ell} + M\left(1 - z_{is}^{jk\ell}\right) \qquad \forall \ell \in \mathcal{T}_{j,k}, j \in \mathcal{O}_s, k \in \mathcal{D}_s, i \in \mathcal{I}_s, s \in \mathcal{S} \tag{10}$$

$$\rho_{is}^k \geq d^{jk\ell} + t^{jk\ell} - M\left(1 - x_{is}^{jk\ell}\right) \qquad \forall \ell \in \mathcal{C}_{j,k}, k \in \mathcal{P} \cup \mathcal{D}_s, j \in \mathcal{F}_k, i \in \mathcal{I}_s, s \in \mathcal{S} \tag{11}$$

$$\rho_{is}^k \geq d^{jk\ell} + t^{jk\ell} - M\left(1 - y_{is}^{jk\ell}\right) \qquad \forall \ell \in \mathcal{R}_{j,k}, k \in \mathcal{P} \cup \mathcal{D}_s, j \in \mathcal{F}_k, i \in \mathcal{I}_s, s \in \mathcal{S} \tag{12}$$

$$\rho_{is}^j \leq d^{jk\ell} x_{is}^{jk\ell} + M\left(1 - x_{is}^{jk\ell}\right) \qquad \forall \ell \in \mathcal{C}_{j,k}, j \in \mathcal{P}, k \in \mathcal{B}_k, i \in \mathcal{I}_s, s \in \mathcal{S} \tag{13}$$

$$\rho_{is}^j \leq d^{jk\ell} y_{is}^{jk\ell} + M\left(1 - y_{is}^{jk\ell}\right) \qquad \forall \ell \in \mathcal{R}_{k,h}, j \in \mathcal{P}, k \in \mathcal{B}_k, i \in \mathcal{I}_s, s \in \mathcal{S} \tag{14}$$

$$\varphi_{is}^k \geq d^{jk\ell} + t^{jk\ell} - M\left(1 - z_{is}^{jk\ell}\right) \qquad \forall \ell \in \mathcal{T}_{j,k}, j \in \mathcal{O}_s, k \in \mathcal{D}_s, i \in \mathcal{I}_s, s \in \mathcal{S} \tag{15}$$

$$\sum_{s \in \mathcal{S}} \sum_{i \in \mathcal{I}_s} V_{is} x_{is}^{jk\ell} \leq \Gamma^{jk\ell} \qquad \forall \ell \in \mathcal{C}_{j,k}, \forall j, k \in \mathcal{N} \tag{16}$$

$$\sum_{s\in\mathcal{S}}\sum_{i\in\mathcal{I}_s} V_{is} y_{is}^{jk\ell} \le \Gamma^{jk\ell} \qquad \forall \ell \in \mathcal{R}_{j,k}, \forall j,k \in \mathcal{N} \tag{17}$$

$$\sum_{s\in\mathcal{S}}\sum_{i\in\mathcal{I}_s} V_{is} z_{is}^{jk\ell} \le \Gamma^{jk\ell} \qquad \forall \ell \in \mathcal{T}_{j,k}, j \in \mathcal{O}_s, k \in \mathcal{D}_s, i \in \mathcal{I}_s, s \in \mathcal{S} \tag{18}$$

$$\sum_{k\in\mathcal{B}_o}\left(\sum_{\ell\in\mathcal{R}_{o,k}} x_{is}^{ok\ell} + \sum_{\ell\in\mathcal{C}_{o,k}} y_{is}^{ok\ell}\right) = w_{is}^{o} \qquad \forall o \in \mathcal{O}_s, \forall i \in \mathcal{I}_s, \forall s \in \mathcal{S} \tag{19}$$

$$\sum_{j\in\mathcal{F}_d}\left(\sum_{\ell\in\mathcal{R}_{j,d}} x_{is}^{jd\ell} + \sum_{\ell\in\mathcal{C}_{j,d}} y_{is}^{jd\ell}\right) = u_{is}^{d} \qquad \forall d \in \mathcal{D}_s, \forall i \in \mathcal{I}_s, \forall s \in \mathcal{S} \tag{20}$$

$$\sum_{\forall o\in\mathcal{O}_s} w_{is}^{o} = 1 \qquad \forall i \in \mathcal{I}_s, \forall s \in \mathcal{S} \tag{21}$$

$$\sum_{\forall d\in\mathcal{D}_s} u_{is}^{d} = 1 \qquad \forall i \in \mathcal{I}_s, \forall s \in \mathcal{S} \tag{22}$$

$$\sum_{j\in\mathcal{F}_p}\left(\sum_{\ell\in\mathcal{R}_{j,p}} x_{is}^{jp\ell} + \sum_{\ell\in\mathcal{C}_{j,p}} y_{is}^{jp\ell}\right) = \sum_{k\in\mathcal{B}_p}\left(\sum_{\ell\in\mathcal{R}_{p,k}} x_{is}^{pk\ell} + \sum_{\ell\in\mathcal{C}_{p,k}} y_{is}^{pk\ell}\right) \qquad \forall i \in \mathcal{I}_s, \forall s \in \mathcal{S}, p \in \mathcal{P} \tag{23}$$

$$x_{is}^{jk\ell}, y_{is}^{jk\ell}, z_{is}^{jk\ell} \in \{0,1\} \tag{24}$$

Constraints (5) and (6) state that the delivery time of a shipment s at the destination terminal $k \in \mathcal{O}_s$ must be greater or equal than the delivery time of each of its units at the terminal whether they are sent directly by trucks (5) or by train and trucks through PI-hubs (6). Constraint (7) state that any generic shipment s arrives at the destination distribution center with an additional delay corresponding to the travel time from the destination terminal. Constraints (8)-(10) guarantee that modules can be assigned only to a truck, a train, or a direct truck departing after their arrival at the origin terminal. Constraints (11) and (12) define the arrival time of any generic module i at any intermediate PI-hub by means of the transport mode ℓ; in particular, (11) defines the arrival time of the module i by truck, whereas (12) defines the arrival time of the module i by train. Constraints (13) and (14) state that, in any PI-hub, modules cannot be assigned to a truck or a to a train, respectively, departing before their arrival at the PI-hub. Constraint (15) define the delivery time at the destination terminals of the modules that are sent directly by trucks. Constraints (16)-(18) guarantee that the assigned modules do not exceed the capacity of modes. Constraints (19) and (20) guarantee that at least a transport mode is assigned to each module. Constraints (21) and (22) guarantee that each module is assigned to one and only one origin and to one and only one destination terminal. Constraint (23) guarantees that all modules, either dispatched via PI-hubs or sent entirely by trucks, reach their destinations, i.e., any modules reaching a node must leave it. Finally, constraints (24) define the integer variables of the problem.

5. Application

The proposed model has been applied to a case study to evaluate its effectiveness and performance. The considered case study is made up of both real data (terminal locations and travel times) and generated/assumed data (demand, fleet size, and shipment volumes). The considered network, shown in Figure 3, consists of one origin terminal, 2 destination terminals, and 3 intermediate PI-hubs. Shipments can be transported from the origin to the destination terminal in two different ways, directly by truck, without any intermediate transshipment, and via the PI-hubs using a combination of trains and trucks. Each PI-hub can send or receive shipments by trains or trucks. The vehicles incoming and outgoing from the PI-hubs can be trains, trucks, or a combination of both; 5 trains and 5 capacitated trucks are available in each route segment (in the first segment the trains/trucks commute between terminal A and PI-hubs, and in the second segment they commute between the PI-hubs and the terminals B and C). In this network, five shipments are considered as an experimental sample and each of them contains five modules. A shipment is delivered to its final destination only once all its modules are delivered. Trains operate on a 2-hour time interval. It is worth pointing out that trucks and trains have different capacities and travel times, and PI-hubs have varying operation times. On the other hand, five trucks directly connect the terminals. This is another option of transportation for the modules or shipments that need to be delivered faster. On the other hand, the operation times of the three PI-hubs are 2, 5, and 7 hours/module, respectively. The values of the model parameters are shown in Table 2 and the costs of each transportation mode for each unit of the modules are in Tables 3 to 7. The costs are calculated based on elements such as distances, transportation modes, and types of trucks/trains.

Table 2. Values of the main model parameters.

Symbol	Description	Value
$\lvert\mathcal{R}_{jk}\rvert$	Number of trains available in each route segment (j,k)	5
$\lvert\mathcal{C}_{jk}\rvert$	Number of trucks available in each route segment (j,k)	5
$\lvert\mathcal{T}_{AB}\rvert = \lvert\mathcal{T}_{AC}\rvert$	Number of direct trucks available in the network	5
$\lvert\mathcal{S}\rvert$	Number of shipments to deliver	5
$\lvert\mathcal{I}_s\rvert$	Number of modules for each shipment *s*	5
t_p	Operation time of the three PI-hubs *p* [hours]	2, 5, 7
$\Gamma^{jk\ell}, \ell \in \mathcal{R}_{jk}$	Capacities in any route segment (j,k) [m^3]	50, 75, 100, 125, 150
$\Gamma^{jk\ell}, \ell \in \mathcal{C}_{jk}$	Truck capacities in each route segment (j,k) [m^3]	14, 15, 16, 17, 13
$\Gamma^{ik\ell}, \ell \in \mathcal{T}_{AB}$ $\Gamma^{ikm}, m \in \mathcal{T}_{AC}$	Capacities of all the direct trucks [m^3]	15, 14, 16, 17, 14
$t_{AB}^{\ell}, \ell \in \mathcal{T}_{\mathrm{AB}}$	Travel times of the direct trucks from terminal A to terminal B [hours]	11.6, 12.5, 12.0, 10.9, 12.1
$t_{AC}^{\ell}, \ell \in \mathcal{T}_{\mathrm{AC}}$	Travel times of the direct trucks from terminal A to terminal C [hours]	14.1, 14.5, 13.9, 15, 14.8
V_{i1}	The volume of the modules in the 1st shipment	4, 6, 3, 4, 5
V_{i2}	The volume of the modules in the 2nd shipment	3, 2, 5, 6, 5
V_{i3}	The volume of the modules in the 3rd shipment	5, 4, 8, 3, 2
V_{i4}	The volume of the modules in the 4th shipment	6, 5, 4, 8, 2
V_{i5}	The volume of the modules in the 5th shipment	7, 6, 6, 6, 5
α, β, γ	Weighting coefficients in the objective function	1, 1, 1

Table 3. Costs (per module) of trains in the segment origin terminal-PI-hubs (€).

	PI-hub A	PI-hub B	PI-hub C
Cost of using train 1 from terminal A to PI-hubs	25	58	66
Cost of using train 2 from terminal A to PI-hubs	36	57	39
Cost of using train 3 from terminal A to PI-hubs	25	38	23
Cost of using train 4 from terminal A to PI-hubs	57	26	74
Cost of using train 5 from terminal A to PI-hubs	46	78	44

Table 4. Costs (per module) of trains in the segment PI-hubs-destination terminals (€).

	Terminal B	Terminal C
Cost of using train 1 from PI-hub A to destination terminals	12	25
Cost of using train 1 from PI-hub B to destination terminals	28	24
Cost of using train 1 from PI-hub C to destination terminals	36	26
Cost of using train 2 from PI-hub A to destination terminals	36	56
Cost of using train 2 from PI-hub B to destination terminals	36	32
Cost of using train 2 from PI-hub C to destination terminals	36	24
Cost of using train 3 from PI-hub A to destination terminals	25	85
Cost of using train 3 from PI-hub B to destination terminals	46	35
Cost of using train 3 from PI-hub C to destination terminals	76	65
Cost of using train 4 from PI-hub A to destination terminals	55	66
Cost of using train 4 from PI-hub B to destination terminals	35	85
Cost of using train 4 from PI-hub C to destination terminals	87	68
Cost of using train 5 from PI-hub A to destination terminals	67	68
Cost of using train 5 from PI-hub B to destination terminals	68	64
Cost of using train 5 from PI-hub C to destination terminals	74	59

Table 5. Costs (per module) of trucks in the segment PI-hubs-destination terminals (€).

	PI-hub A	PI-hub B	PI-hub C
Cost of using truck 1 from terminal A to PI-hubs	850	817	1764
Cost of using truck 2 from terminal A to PI-hubs	750	721	1557
Cost of using truck 3 from terminal A to PI-hubs	950	673	1972
Cost of using truck 4 from terminal A to PI-hubs	800	769	1660
Cost of using truck 5 from terminal A to PI-hubs	700	913	1950

Table 6. Costs (per module) of trucks in the segment PI-hubs-destination terminals (€).

	Terminal B	Terminal C
Cost of using truck 1 from PI-hub A to destination terminals	1364	2246
Cost of using truck 1 from PI-hub B to destination terminals	1840	1561
Cost of using truck 1 from PI-hub C to destination terminals	2441	1534
Cost of using truck 2 from PI-hub A to destination terminals	1108	1964
Cost of using truck 2 from PI-hub B to destination terminals	1925	1480
Cost of using truck 2 from PI-hub C to destination terminals	2564	1620
Cost of using truck 3 from PI-hub A to destination terminals	1530	2469
Cost of using truck 3 from PI-hub B to destination terminals	1782	1637
Cost of using truck 3 from PI-hub C to destination terminals	2203	1258
Cost of using truck 4 from PI-hub A to destination terminals	1106	2122
Cost of using truck 4 from PI-hub B to destination terminals	1790	1386
Cost of using truck 4 from PI-hub C to destination terminals	2323	1591
Cost of using truck 5 from PI-hub A to destination terminals	1240	2054
Cost of using truck 5 from PI-hub B to destination terminals	2020	1669
Cost of using truck 5 from PI-hub C to destination terminals	2122	1534

Table 7. Costs (per module) of direct trucks in the network (€).

	Terminal B	Terminal C
Cost of using direct truck 1 from terminal A to destination terminals	3472	3798
Cost of using direct truck 2 from terminal A to destination terminals	3658	3897
Cost of using direct truck 3 from terminal A to destination terminals	3365	3963
Cost of using direct truck 4 from terminal A to destination terminals	3561	3723
Cost of using direct truck 5 from terminal A to destination terminals	3453	3636

The facilities are assumed to be in Europe. As shown in Figure 2, the origin terminal A (in green) is assumed to be in Rotterdam (Netherland), the three PI-hubs (in blue) in Hamburg (Germany), Mannheim (Germany), and Milan (Italy), and the destination terminals B and C (in red) in Budapest (Hungary) and Warsaw (Poland), respectively. The distances between the considered facilities have been measured by google maps in order to calculate the travel times and the cost of transport per segment.

The proposed MILP model has been implemented and solved with CPLEX Studio. The experiments were conducted on a workstation equipped with an Intel® Core™ i7-CPU running at 3.30 GHz and 16.00 GB of RAM.

The model has been solved, firstly, with a fixed configuration (shown in Table 2) of the model parameters to obtain a reference solution; this solution, showed in Tables 8, 9, and 10, is then used as reference in Section 5.1, to discuss the effects on the solution of a variation of the truck capacity, and of a change in the relative importance of the three objectives. In particular, Table 8 shows the value of the objectives and the number of times a train or truck has been used in the route segment; Table 9 shows the truck and the destination terminal associated with each module that was assigned to a direct truck; Table 10 shows, for each module, the associated train, PI-hub and destination terminal in the first and second route segment. In Tables 9 and 10, the first two columns indicate the number of the specific module and shipment. For instance, the first row of Table 9 indicates that module 5 of shipment 4 is assigned to the direct truck 2 and transported to the destination terminal C.

As it emerges from Tables 8 to 10, upon solving the proposed model using the provided data, 12 modules are allocated to direct trucks towards terminal C. Terminal B is never used since the travel times towards it are higher (Table 2). Additionally, 13 modules are dispatched via PI-hubs located in Hamburg and Milan (1 and 3). These modules are sent to the PI-hubs, and are transported by trains 1 and 3 in the segment between origin terminal A and PI-hubs, and trains 1 and 2 in the segment between PI-hubs and destination terminals. It is worth pointing out that the PI paradigm allowed by the model is exploited, since some shipments are unpacked, moved with different transport means, and then assembled again at the destination terminal. For instance, modules 1 and 2 of the shipment 1 are sent (Table 9) to the destination terminal C by direct trucks, i.e. bypassing the PI-hubs, while the other three modules are moved by trains through the PI-hub 1 on both the route segments.

In addition, it is possible to see that the truck option is never used on the route segments. This is justified by the higher transportation costs associated with this option.

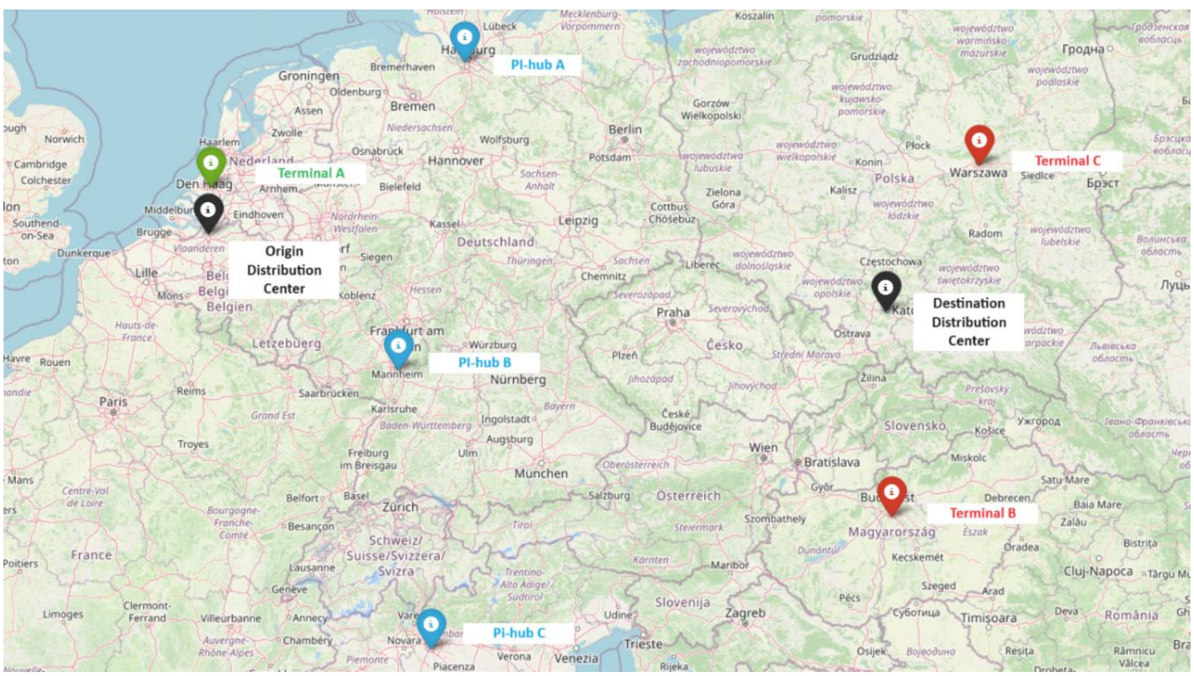

Figure 3. The assumed locations of the facilities in Europe: in green the origin terminal, in blue the three PI-hubs, in red the two destination terminals, and in black the distribution centers.

Table 8. The value of the objectives and variables.

Direct truck usage (J_1)	Total delivery time (J_2)	Total transportation costs (J_3)	Trucks in segment Origin Terminal-PI-hubs	Trains in segment Origin Terminal-PI-hubs	Trucks in segment PI-hubs-Destination Terminals	Trains in segment PI-hubs-Destination Terminals
12	213.22	635	0	13	0	13

5.1 Sensitivity analysis

This section presents the results of a sensitivity analysis conducted with the aim of evaluating the impact of model parameters on the solution. In particular, the selected parameters are the capacity of trucks and the weighting coefficients of the objective function. The motivation is to study, given a case study (i.e. assuming all parameters indicating the demand, the costs, and the travel times are known and fixed), how the model reacts to a change in the supply system, and how it can find different solutions by altering the priorities of the three objectives in the objective function.

Table 9. Order of shipments and modules sent by direct trucks.

Module	Shipment	Truck	Destination Terminal
5	4	2	C
5	3	3	C
5	1	4	C
4	3	2	C
4	1	3	C
3	4	4	C
3	1	5	C
2	3	5	C
2	2	4	C
2	1	1	C
1	2	1	C
1	1	2	C

Table 10. Order of shipments and modules sent through the PI-hubs by the trains.

Module	Shipment	Trains in segment Origin Terminal-PI-hubs	PI-hub	Trains in segment PI-hubs-Destination Terminals	Destination Terminal
5	5	3	3	2	C
4	5	3	3	2	C
3	5	3	3	2	C
2	5	3	3	2	C
1	5	3	3	2	C
5	2	1	1	1	C
4	4	1	1	1	C
4	2	1	1	1	C
3	3	1	1	1	C
3	2	1	1	1	C
2	4	1	1	1	C
1	4	1	1	1	C
1	3	1	1	1	C

As for the first objective, since the road mode is usually associated with a higher degree of flexibility in terms of the number of operators and vehicle types, the first analysis is aimed at assessing the effect of the variation of truck capacity, while keeping the capacity of the trains constant. As a matter of fact, road transport can react more quickly to the market needs, and since it is often a competitor of the railway mode it can be important to consider its differences with respect to the railway mode in an optimization problem. As a matter of fact, road transport can react more quickly to the market needs, and since it is often a competitor of the railway mode, it is important to consider possible variations in its capacity in the optimization problem.

Results are shown in Table 11, where the reference solution (obtained by using the parameter values shown in Table 2) is marked in bold. It is possible to see a logical correlation between variations in the direct truck capacity and their corresponding usage, as indicated by the J_1 value: increasing trucks capacities leads to an increase in their usage. Additionally, an increase in the capacity of direct trucks results also in a decrease of the total delivery times (J_1) and transportation costs (J_3). On the other hand, the number of transfers by train (columns 7 and 9) decreases accordingly. These results are further illustrated in Fig 4. As it is possible to see from the last column of Table 11, the computational time was always acceptable, even if it is expected to increase for larger case studies.

Table 11. Variation of the objectives depending on the capacities of the direct trucks.

Capacity variation of direct trucks	Direct truck usage (J_1)	Total delivery time (J_2)	Total transportation costs (J_3)	Trucks in segment Origin Terminal-PI-hubs	Trains in segment Origin Terminal-PI-hubs	Trucks in segment PI-hubs-Destination Terminals	Trains in segment PI-hubs-Destination Terminals	Solution time (s)
-80%	2	280.82	1120	0	23	0	23	17.9
-60%	5	280.82	970	0	20	0	20	6.9
-40%	9	261.76	788	0	16	0	16	8.3
-20%	10	213.22	735	0	15	0	15	4.0
-	**12**	**213.22**	**635**	**0**	**13**	**0**	**13**	**13.7**
+20%	14	145.62	550	0	11	0	11	5.1
+40%	16	145.62	450	0	9	0	9	4.2
+60%	17	116.64	385	0	8	0	8	3.2
+80%	19	145.62	300	0	6	0	6	15.3

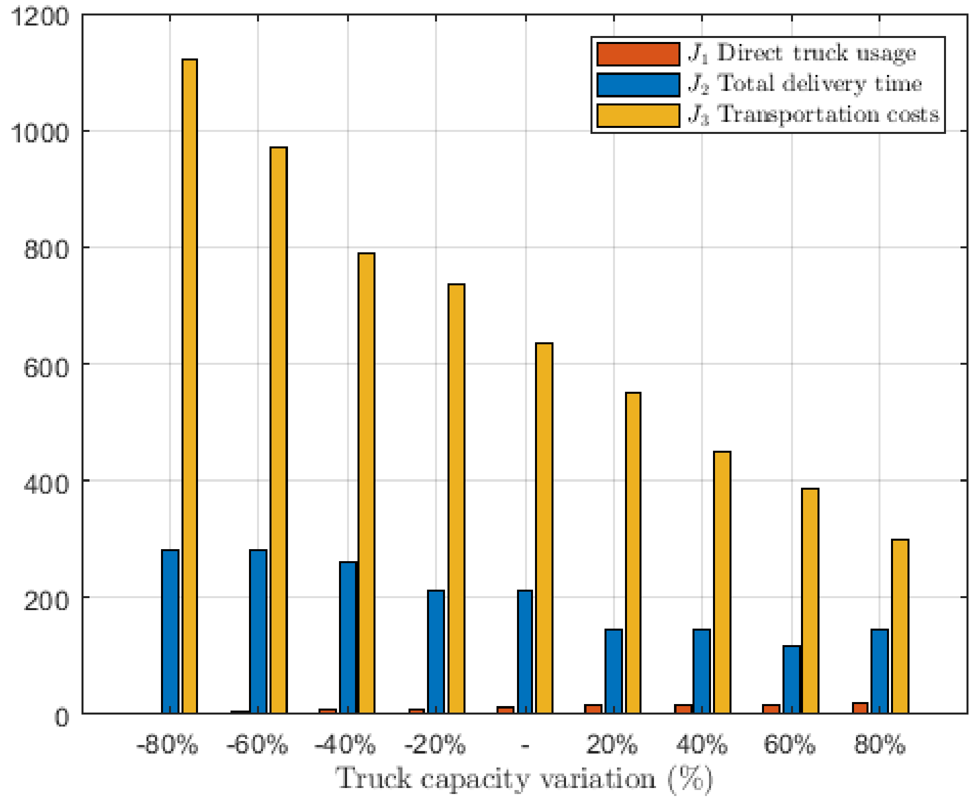

Figure 4. Variation of the objectives depending on the capacities of the direct trucks.

The second analysis is aimed at testing the effect of the variation of the coefficients α, β, and γ on the objectives J_1, J_2, and J_3; by varying the coefficient values, the objective significance in the problem can be customized to yield logical and desired solutions. The results are shown in Table 12 and Figure 5, Figure 6, and Figure 7: it is possible to observe that, as expected, increasing the value of a weighting coefficient (while keeping constant the other ones) results in a decrease in the value the associated objective. This is expected as the problem is formalized as a minimization one. This highlights the trade-off among the proposed objectives, as optimizing one can have implications for the others. For example, prioritizing the minimization of the direct truck usage results in an increase in the total delivery times and of the resulting transportation costs. The former increases in a non-linear way with respect to the value of α, as it remains constant up to a certain average prioritization of the truck usage (Table 12, row 2), whereas it increases significantly when the first objective is highly prioritized (Table 12, row 5). On the other hand, the latter increases linearly with the value of α. Another observation is that the increase in the importance of the delivery time leads to an increase in the transportation costs; in particular, a 30% decrease in the total delivery times increases the total transportation cost up to 20% (Table 12, row 6). In summary, these results confirm that the delivery times and the transportation costs are, in the considered scenario, in conflict. In a real-world application, the values of the parameters should be chosen accordingly with the desired goals and external constraints (e.g., carbon tax).

Table 12. Objective values as a function of the coefficients of the related objective.

α	β	γ	Direct truck usage (J_1)	Total delivery time (J_2)	Total transportation costs (J_3)	Trucks in segment Origin Terminal-PI-hubs	Trains in segment Origin Terminal-PI-hubs	Trucks in segment PI-hubs-Destination Terminals	Trains in segment PI-hubs-Destination Terminals
1	1	1	12	213.2	635	0	13	0	13
5	1	1	5	213.72	985	0	20	0	20
1	5	1	10	150.38	750	0	15	0	15
1	1	5	12	251.34	616	0	13	0	13
10	1	1	0	299.88	1207	0	25	0	25
1	10	1	10	149.88	761	0	15	0	15
1	1	10	12	270.4	615	0	13	0	13

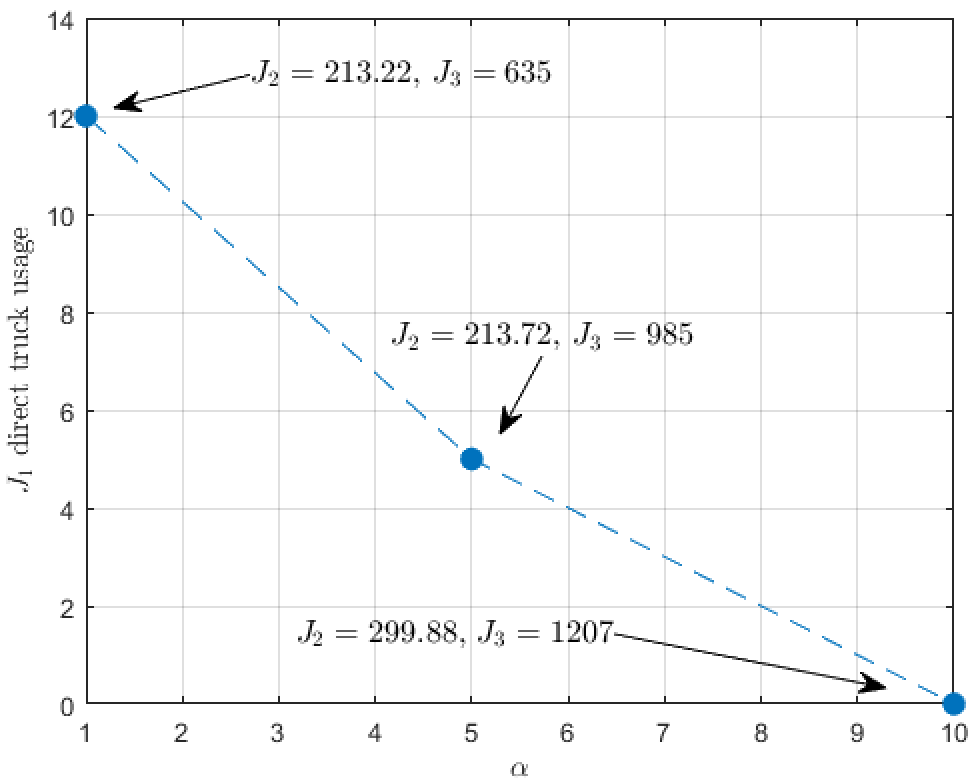

Figure 5. Variation of the objectives as a function of the first objective coefficient.

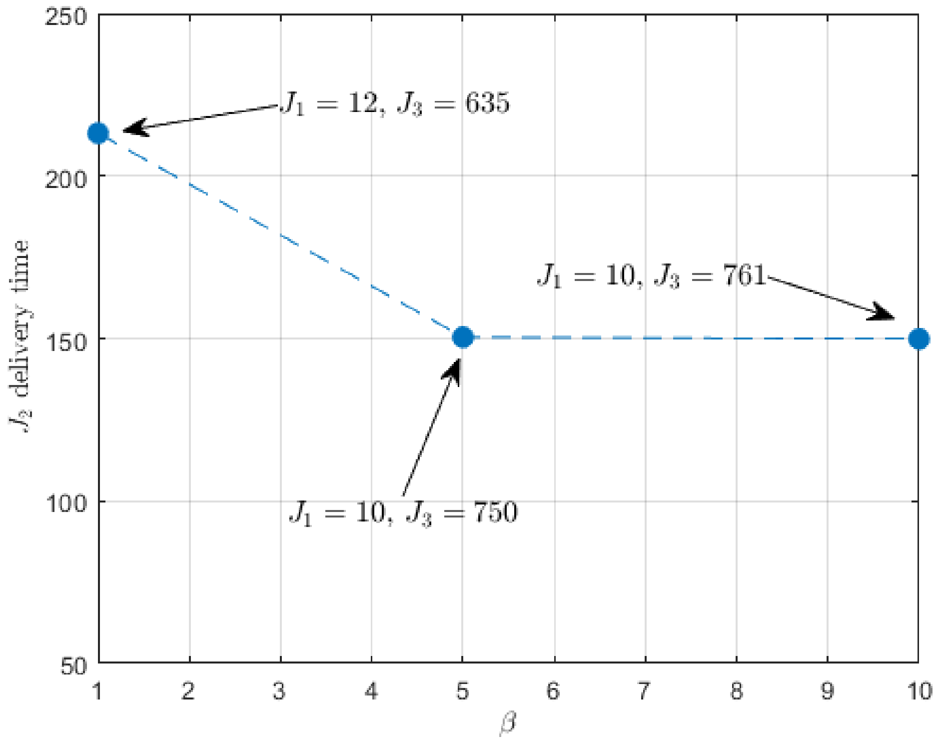

Figure 6. Variation of the objectives as a function of the second objective coefficient.

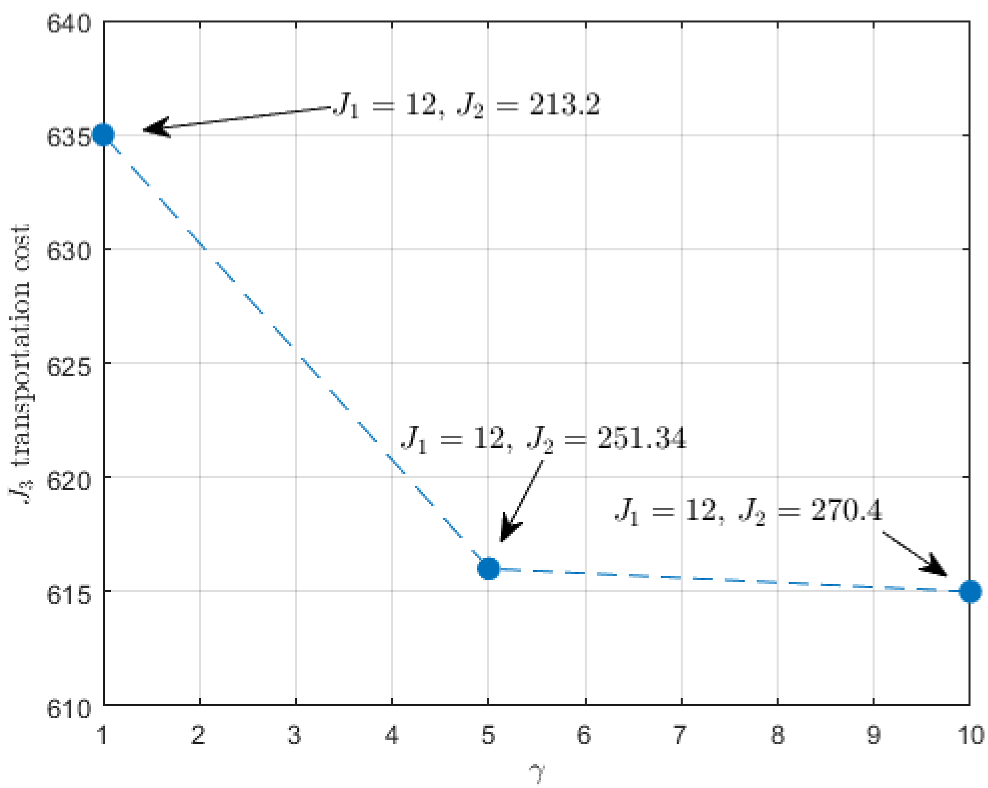

Figure 7: Variation of the objectives as a function of the third objective coefficient.

In conclusion, the results shows that the proposed optimization model is able to consider the PI paradigm within the addressed freight transportation network. As stated previously, this characteristics is among the main novelty of this paper: shipments are effectively divided into modules, which are transported with different transportation means according to the optimal solution provided by the optimization problem; all the modules reaches their destinations and are reassembled together within the fixed time (i.e., the lead times are always met). While doing so, the direct truck usage, the delivery times, and the transportation costs are minimized. The weighting coefficients in the objective function allow to set priorities among the three objectives, according to external needs.

6. Conclusions

This paper addressed the optimization of a freight transport network that contains various facilities for efficiently moving shipments from suppliers to customers, allowing to disassemble and reassemble shipments into modules according to the principles of the PI paradigm. In particular, the focus was on the optimization of the flow of shipments between the designated terminals within the network. Two options for managing the shipment flow were allowed: transporting the shipments through designated PI-hubs by means of trains or trucks, and direct truck transportation between terminals. Each PI-hub splits the modules and directs them to the appropriate terminal. The modules in each PI-hub can be sent or received by either trucks or trains. The expected output of the model was to determine the most efficient mode allocation strategy for the modules, and whether to dispatch them directly via trucks or route them through strategically located PI-hubs.

The optimization model was formulated as a mixed-integer linear programming (MILP) problem and was subsequently applied to a simplified scenario to test its feasibility and performance. The results of the conducted analyses reveal that the model can effectively allocate the modules of the shipments according to the available resources and the desired objectives. In particular, the PI paradigm was effectively exploited since some modules are sent in parallel using different vehicles and reassembled together at the destination terminal. This ensures the optimal distribution of modules, optimizing transportation efficiency and resource utilization. The paper ends with a sensitivity analysis aimed at verifying the impact of some parameters on the solution, such as the truck capacity and the weighting coefficients of the objective function. The results are grounded in logic, since reducing truck capacity prompts a shift in freight flow towards trains via the PI-hubs, and an increase in the weighing coefficient of an objective leads to an increase in other objective values.

The model is sufficiently general, and could be applied to different network configurations, with different topologies, transportation modes, number of terminals and PI-hubs and time windows. While doing so, its main limitation lies in the computational times, which were definitely acceptable in the considered application, but that are expected to increase with the size and complexity of the network: for this reason, a future extension of this work will address the development of a heuristic method to tackle large-scale problems. Other extensions will deal with expanding the scope of the model to encompass an entire network rather than focusing solely on the section between terminals, and with including the uncertainty related to some parameters (such as, for example, the travel and operation times, and the costs of the transportation modes) that is inherent in real-world scenarios.

Acknowledgement

"Funded by European Union - NextGenerationEU. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or European Commission. Neither the European Union nor the European Commission can be held responsible for them."

References

Ballot, E., Gobet, O., & Montreuil, B. (2012). Physical internet enabled open hub network design for distributed networked operations. *Service orientation in holonic and multi-agent manufacturing control*, 279-292.

Ballot, E., Montreuil, B., & Fontane, F. (2011). Topology of logistic networks and the potential of a physical internet. International Conference on Industrial Engineering and Systems Management IESM.

Ballot, E., Montreuil, B., & Meller, R. D. (2014). *The physical internet*: La Documentation Française.

Ballot, E., Montreuil, B., & Thivierge, C. (2012). Functional design of physical internet facilities: a road-rail hub.

Ben Mohamed, I., Klibi, W., Labarthe, O., Deschamps, J.-C., & Babai, M. Z. (2017). Modelling and solution approaches for the interconnected city logistics. *International Journal of Production Research*, *55*(9), 2664-2684.

Boussedjra, M., Bloch, C., & El Moudni, A. (2004). An exact method to find the intermodal shortest path (ISP). IEEE International Conference on Networking, Sensing and Control, 2004.

Briand, M., Franklin, R., & Lafkihi, M. (2022). A dynamic routing protocol with payments for the Physical Internet: A simulation with learning agents. *Transportation Research Part E: Logistics and Transportation Review*, *166*, 102905

Chargui, T., Bekrar, A., Reghioui, M., & Trentesaux, D. (2019). Multi-objective sustainable truck scheduling in a rail–road physical internet cross-docking hub considering energy consumption. *Sustainability*, *11*(11),3127.

Chargui, T., Ladier, A.-L., Bekrar, A., Pan, S., & Trentesaux, D. (2022). Towards designing and operating physical internet cross-docks: Problem specifications and research perspectives. *Omega, 111*,102641.

Crainic, T. G., & Kim, K. H. (2007). Intermodal transportation. *Handbooks in operations research and management science*, *14*, 467-537.

Dong, C., & Franklin, R. (2021). From the digital Internet to the physical Internet: A conceptual framework with a stylized network model. *Journal of Business Logistics*, *42*(1), 108-119.

European Commission. (2023). Green Deal: Greening freight for more economic gain with less environmental impact.

Fazili, M., Venkatadri, U., Cyrus, P., & Tajbakhsh, M. (2017). Physical Internet, conventional and hybrid logistic systems: a routing optimisation-based comparison using the Eastern Canada road network case study. *International Journal of Production Research, 55*(9), 2703-2730.

Huang, Y. (2021). A Two-Stage Stochastic Model for Intermodal Transportation Operational Planning Problem Under Capacity Shortage. *2021 IEEE International Conference on Recent Advances in Systems Science and Engineering* (RASSE) (pp. 1-9). IEEE.

Kaup, S., Ludwig, A., & Franczyk, B. (2020). Design and Evaluation of Routing Artifacts as a Part of the Physical Internet Framework. *arXiv preprint arXiv, 2011, 09972*.

Lemmens, N., Gijsbrechts, J., & Boute, R. (2019). Synchromodality in the Physical Internet–dual sourcing and real-time switching between transport modes. *European Transport Research Review*, *11*, 1-10.

Lin, Y.-H., Meller, R. D., Ellis, K. P., Thomas, L. M., & Lombardi, B. J. (2014). A decomposition-based approach for the selection of standardized modular containers. *International Journal of Production Research, 52*(15), 4660-4672.

Meller, R. D., Montreuil, B., Thivierge, C., & Montreuil, Z. (2012). Functional design of physical internet facilities: a road-based transit center.

Montreuil, B. (2011). Toward a Physical Internet: meeting the global logistics sustainability grand challenge. *Logistics Research*, *3*, 71-87.

Montreuil, B., Meller, R. D., & Ballot, E. (2010). Towards a Physical Internet: the impact on logistics facilities and material handling systems design and innovation.

Montreuil, B., Meller, R. D., Thivierge, C., & Montreuil, Z. (2013). *Functional design of physical internet facilities: a unimodal road-based crossdocking hub,* CIRRELT Montreal, Canada.

Napolitano, M. (2000). *Making the move to cross docking: A practical guide to planning, designing, and implementing a cross dock operation,* Warehousing Education and Research Council.

Onal, S., Zhang, J., & Das, S. (2018). Product flows and decision models in Internet fulfillment warehouses. *Production Planning & Control, 29*(10), 791-801.

Pan, S., Nigrelli, M., Ballot, E., Sarraj, R., & Yang, Y. (2015). Perspectives of inventory control models in the Physical Internet: A simulation study. *Computers & Industrial Engineering*, *84*, 122-132.

Qu, W., Rezaei, J., Maknoon, Y., & Tavasszy, L. (2019). Hinterland freight transportation replanning model under the framework of synchromodality. *Transportation Research Part E: Logistics and Transportation Review*, *131*, 308-328.

Reis, V. (2014). Analysis of mode choice variables in short-distance intermodal freight transport using an agent-based model. *Transportation Research Part A: Policy and Practice*, *61*, 100-120.

Saeed, N. (2013). Cooperation among freight forwarders: Mode choice and intermodal freight transport. *Research in Transportation Economics*, *42*(1), 77-86.

Sallez, Y., Pan, S., Montreuil, B., Berger, T., & Ballot, E. (2016). On the activeness of intelligent Physical Internet containers. *Computers in Industry*, *81*, 96-104.

Sarraj, R., Ballot, E., Pan, S., Hakimi, D., & Montreuil, B. (2014). Interconnected logistic networks and protocols: simulation-based efficiency assessment. *International Journal of Production Research*, *52*(11),3185-3208.

Sawadogo, M., Anciaux, D., & Daniel, R. (2012). Reducing intermodal transportation impacts on society and environment by path selection: a multiobjective shortest path approach. *IFAC Proceedings Volumes*, *45*(6), 505-513.

Sun, Y., Zhang, C., Dong, K., & Lang, M. (2018). Multiagent modelling and simulation of a physical internet enabled rail-road intermodal transport system. *Urban Rail Transit*, *4*, 141-154.

Venkatadri, U., Krishna, K. S., & Ülkü, M. A. (2016). On Physical Internet logistics: modeling the impact of consolidation on transportation and inventory costs. *IEEE Transactions on Automation Science and Engineering*, *13*(4), 1517-1527.

Walha, F., Bekrar, A., Chaabane, S., & Loukil, T. M. (2016). A rail-road PI-hub allocation problem: Active and reactive approaches. *Computers in Industry, 81*, 138-151.

Zhang, J., Ding, H. W., Wang, X. Q., Yin, W. J., Zhao, T. Z., & Dong, J. (2011). Mode choice for the intermodal transportation considering carbon emissions. Proceedings of 2011 IEEE International Conference on Service Operations, Logistics and Informatics.

Zhang, J., Zhang, Q., & Zhang, L. (2015). A study on the paths choice of intermodal transport based on reliability. LISS 2014: Proceedings of 4th International Conference on Logistics, Informatics and Service Science.

Zhang, Y., Lin, B., Liang, D., & Gao, H. (2006). Research on a generalized shortest path method of optimizing intermodal transportation problems. *Journal of the China Railway Society*, *28*(4), 22-26.

Zhong, R. Y., Xu, C., Chen, C., & Huang, G. Q. (2017). Big data analytics for physical internet-based intelligent manufacturing shop floors. *International Journal of Production Research*, *55*(9), 2610-2621.