Lead-time-based Routing of Freight in PI Networks

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Introduction

Freight transport sector is responsible for a substantial share of carbon emissions (Lemmens et al.,2019) and considering its growth and reliance on fossil fuels, reducing this share seems challenging (McKinnon, 2018). Transitioning to a low-carbon economy requires a joint effort in decarbonizing road transport and fostering a modal shift towards the more sustainable option of rail transport (McKinnon, 2016).

However, in practice, lack of flexibility in delivery quantity, frequency, and strict scheduling are major barriers to the attractiveness of intermodal transport (Meers et al., 2017). Horizontal integration of different transport modes, as in synchronized intermodality (Tavasszy et al., 2017), allows for parallel deployment of different transport modes, where intermodal transport is one of them.

To substantially increase the efficiency and sustainability of logistics, the concept of physical internet (PI) was introduced by (Montreuil, 2011) based on the digital, operational, and physical interconnectivity of global logistic systems (Meller et al.,2012). Inspired by the data packets in the digital internet, the idea of PI is that products are dispatched in special standard containers. In this regard, Montreuil et al. (2010) introduced three main elements of PI as PI-containers, PI-nodes (e.g., PI-hubs, PI-sorters, etc.), and PI-movers (PI-conveyors, PI-vehicles, etc.). In PI-hubs, arriving PI-containers are transferred to the (same or different) departure modes. As an essential component of the PI-network, PI-hubs have been studied in the context of intermodal transport. (Chargui et al., 2019) considered a MILP to optimize the operations in a rail-road PI-hub cross-dock terminal. They minimized the energy consumption for the PI-conveyors used in the PI-hub and the cost of using outbound trucks. (Essghaier et al., 2022) proposed a multi-objective truck-scheduling problem in rail-road PI-hubs considering uncertainty. They utilized the Fuzzy Multi-objective MIP approach to cope with uncertainties. They optimized the truck's delay as well as the travel distances of the PI-containers in PI-hubs.

This study explores PI-based synchronized transport of standard containers of various sizes where intermodal transport is considered horizontally alongside direct trucking. To ensure increased sustainability, the approach seeks minimizing the number of trucks required to transport goods. The proposed model is inspired by the work by (Di Febbraro et al, 2016) to plan intermodal transport chains in a cooperative manner. They considered three sets of sub-problems to optimize the entire intermodal chain.

Problem Definition

In this section, the modeling framework is presented where shipments are transferred using two alternative transportation modes:

1. Rail and truck via PI-hub: It is assumed that the rail schedule is created to accommodate the demand and to create economies of scale. The rail-road PI-hub represents a class of PI-nodes that facilitates the transfer of PI-containers delivered by trains to trucks departing from the site. It incorporates a PI-sorter and two maneuvering zones situated at the train and loading dock sections. The cross-docking procedure commences with the unloading of PI-containers from the wagons, followed by their categorization by destination and delivery to the designated outbound docks. Finally, the PI-containers are loaded onto the outgoing trucks and the trucks deliver them to their related nodes.

2. Only direct trucks: This mode is much faster than the previous one, but it is not much sustainable and also imposes more cost on the transportation chain. Hence, the model seeks minimizing the number of trucks with the same destination by utilizing truck capacities while respecting the delivery time of shipments. As modular containers are assumed, the delivery time of a shipment is equal to the delivery time of its last module.

Other assumptions include:

- The considered shipping flow is only the one from node A to node B.
- The trains of the first transportation mode are scheduled and depart from node A.
- Trucks are not scheduled but the objective is to use their maximum capacity.
- Each of the modules has a specific operation time in the PI-hub.
- Delivery time of a shipment is equal to delivery time of its last module.

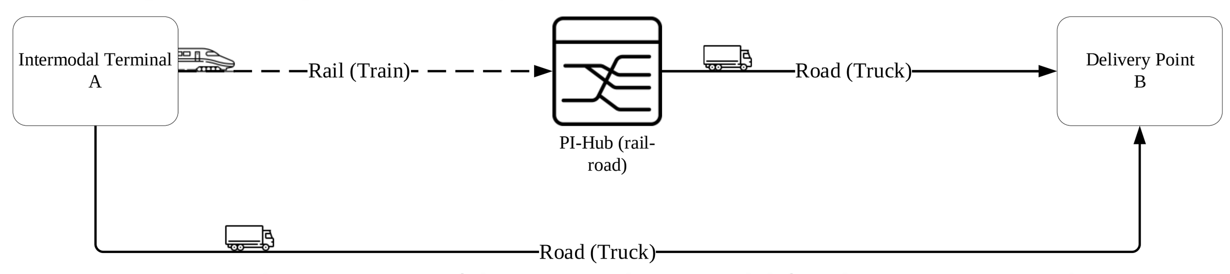

Fig. 1: A schematic view of the proposed intermodal freight transportation chain

Methodology

Optimization Model:

The first and the second objective function minimizes the total number of direct trucks and total delivery time of the modular shipments, respectively.

$$J_1 = \sum_{s\in\mathcal{S}}\sum_{i\in\mathcal{I}_s}\sum_{\ell\in\mathcal{T}} z_\ell^{is} \quad \text{and} \quad J_2 = \sum_{s\in\mathcal{S}} \beta_s \cdot DT_s$$

The combination of the above objective function using weighting coefficients in order to prioritizing them.

$$[z^\star, w^\star, r^\star] = \arg\min[\alpha J_1 + J_2]$$

$s.t.$

$$DT_s \ge \varphi^{is} \qquad \forall i \in \mathcal{I}_s, s\in\mathcal{S}$$
$$DT_s \ge \sigma^{is} \qquad \forall i \in \mathcal{I}_s, s\in\mathcal{S}$$
$$\rho^{is} \ge (d_\ell + tt_\ell)w_\ell^{is} - M(1 - w_\ell^{is}), \qquad \forall \ell\in\mathcal{R}, i \in \mathcal{I}_s, s\in\mathcal{S}$$
$$\sigma^{is} \ge \rho^{is} + t_p^{is} + tt_\ell - M(1 - r_\ell^{is}), \qquad \forall \ell\in\mathcal{C}$$
$$\varphi^{is} \ge Ar_A^s \cdot z_\ell^{is} + tt_\ell - M(1 - z_\ell^{is}), \qquad \forall \ell\in\mathcal{T}$$
$$\sum_{s\in\mathcal{S}}\sum_{i\in\mathcal{I}_s} V^{is} z_\ell^{is} \le Cap_\ell \qquad \forall \ell\in\mathcal{T}$$
$$\sum_{s\in\mathcal{S}}\sum_{i\in\mathcal{I}_s} V^{is} w_\ell^{is} \le Cap_\ell \qquad \forall \ell\in\mathcal{R}$$
$$\sum_{s\in\mathcal{S}}\sum_{i\in\mathcal{I}_s} V^{is} r_\ell^{is} \le Cap_\ell \qquad \forall \ell\in\mathcal{C}$$
$$\sum_{\ell\in\mathcal{R}} w_\ell^{is} + \sum_{\ell\in\mathcal{T}} z_\ell^{is} = 1 \qquad \forall i \in \mathcal{I}_s, \forall s\in\mathcal{S}$$
$$\sum_{\ell\in\mathcal{C}} r_\ell^{is} = \sum_{\ell\in\mathcal{R}} w_\ell^{is} \qquad \forall i \in \mathcal{I}_s, \forall s\in\mathcal{S}$$
$$z_\ell^{is}, w_\ell^{is}, r_\ell^{is} \in \{0,1\} \qquad \forall i \in \mathcal{I}_s, \forall s\in\mathcal{S}, \ell\in\mathcal{C}, \ell\in\mathcal{R}, \ell\in\mathcal{T}$$
$$Ar_A^s \ge 0, \qquad DT_s \ge 0 \qquad \forall s\in\mathcal{S}$$

Parameters	
V^{is}	Volume of module i of shipment s
V_s	Volume of the whole shipment s
Cap_ℓ	Capacity of transport mode $\ell \in \mathcal{T} \cup \mathcal{R} \cup \mathcal{C}$
tt_ℓ	Travel time of module i of shipment s with transport mode $\ell \in \mathcal{T} \cup \mathcal{R} \cup \mathcal{C}$
t_p^{is}	Operation time of the module i of shipment s in PI-hub
d_ℓ	Departure time of train $\ell \in \mathcal{T}$
α, β_s	Weight coefficients (s referring to shipments)
Decision variables	
z_ℓ^{is}	1 if module i of the shipment s is assigned to direct truck $\ell \in \mathcal{T}$, and otherwise, 0
w_ℓ^{is}	1 if module i of the shipment s is assigned to train $\ell \in \mathcal{R}$, and otherwise, 0
r_ℓ^{is}	1 if module i of the shipment s is assigned to truck $\ell \in \mathcal{C}$, and otherwise, 0
Other variables	
Ar_A^s	Arrival time of module i of shipment s at node A
DT_s	Delivery time of shipment s to its destination
φ^{is}	Delivery time of module i of shipment s sent by only truck
ρ^{is}	Delivery time of module i of shipment s to the PI-hub
σ^{is}	Delivery time of module i of shipment s sent via train + truck

Computational Results

The optimal value of the cost function ($G^\star = \alpha J_1^\star + J_2^\star$) and the optimal values of $J_1^\star$ (minimum number of trucks), and $J_2^\star$ (minimum weighed delivery time of shipments) for α and β equal to 1 and 0.5, respectively, are presented. In addition, also the train and truck pairs are assigned to the delivery via the PI-hub, and the optimal truck number directly connecting nodes A and B are provided.

	$G^\star$	$J_1^\star$	$J_2^\star$	Number of modules transferred via (train number, truck number)	Number of modules transferred via (truck number)
Optimal value	26.099	3	24.6	22	3

The table below indicates assigning modules of shipments to each transportation mode.

(Module number, Shipment Number)	Intermodal Transport via PI-hub (Train number, Truck number)	Direct Trucking (Truck Number)
(5, 1)	-	3
(3, 2)	-	3
(2, 1)	-	1
(1, 1)	(1, 7)	-
(1, 2)	(1, 4)	-
(1, 3)	(2, 1)	-
(1, 4)	(1, 4)	-
(1, 5)	(2, 5)	-
(2, 2)	(1, 1)	-
(2, 3)	(2, 7)	-
(2, 4)	(1, 5)	-
(2, 5)	(2, 7)	-
(3, 1)	(1, 1)	-
(3, 3)	(2, 2)	-
(3, 4)	(1, 1)	-
(3, 5)	(2, 3)	-
(4, 1)	(1, 3)	-
(4, 2)	(1, 6)	-
(4, 3)	(2, 7)	-
(4, 4)	(1, 6)	-
(4, 5)	(2, 2)	-
(5, 2)	(1, 4)	-
(5, 3)	(2, 4)	-
(5, 4)	(1, 2)	-
(5, 5)	(2, 3)	-

Sensitivity Analysis

The sensitivity analysis was performed by varying the coefficient amounts (α and β) for each objective. As it is shown in Fig. 1 and Fig. 2, the variation of α and β can affect the optimal values of both objectives. In this analysis, the sum of α and β is equal to 1 for all the scenarios.

The first analysis shown in Fig. 2 and Fig. 3 measures the impact of changing α and β on the first objective optimal solutions. As it is illustrated, dropping the amount of α, followed by the rise of β, emerges in the growth of the first objective and a decline in the second objective optimal solutions. That is to say, the number of modules sent by only trucks witnessed a moderate increase, according to the mentioned trend. Also in the same way, the delivery time of the modules would become lower. As depicted in Fig. 2, $J_1^\star$ witnessed significant growth from 3 to 12 in scenario 9 which shows a sensitivity of the graph at this point by varying α and β.

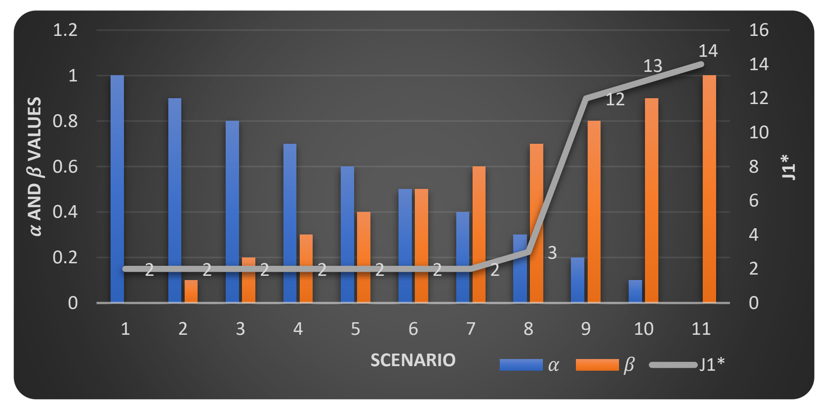

Fig. 2: Sensitivity analysis for α and β on $J_1^\star$

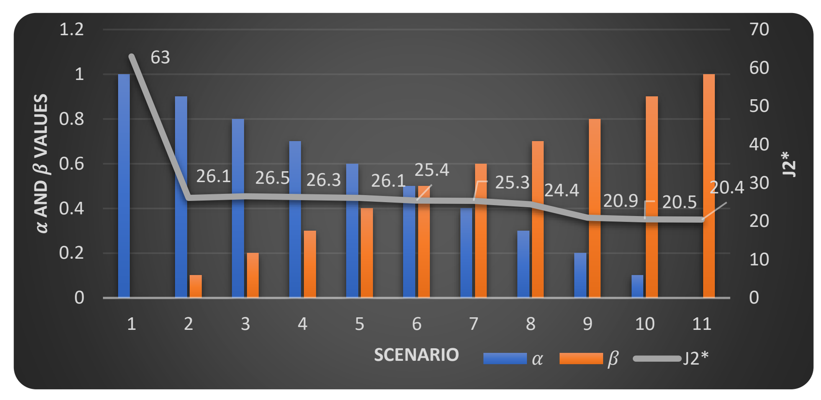

Fig. 3: Sensitivity analysis for α and β on $J_2^\star$

In the second analysis, the impact of the operation time of each module in the PI-hub on the mode choice is considered. This analysis shows that by increasing the operation time of the PI-hub for each module, the preference for selecting the second transportation mode (only trucks) increases and the chain experiences shifting the transportation mode from the first mode to the second one. In this case, 4 scenarios are considered for variation of operating time. As shown, the number of modules sent by the first transportation mode (train + truck) decreased substantially after adding 3 hours to the default operation time for each module. By contrast, in the same scenario, the figure for the modules transferred by the second transportation mode (only trucks) rises significantly, from 3 to 15.

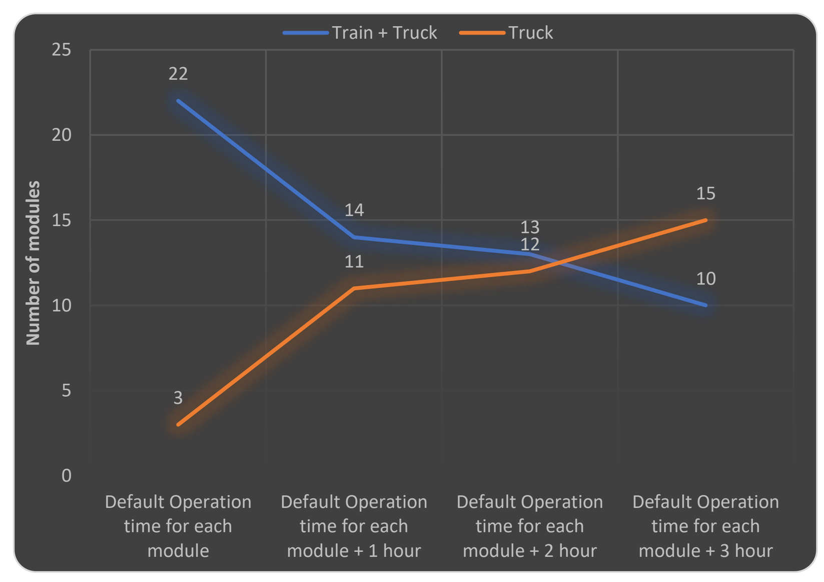

Fig. 4: Sensitivity analysis for the operation time of each module in PI-Hub

Conclusion

This study proposes a PI-based planning model for synchromodal operation of a transport network considering the parallel operation of intermodal and truck-only routes. The proposed multi-objective model seeks to satisfy the delivery time of goods while minimizing the number of trucks. The results obtained from the implementation and analysis of the model show the interplay between the importance of delivery time versus the environmental impact of transporting goods. However, it is possible to find a spot where these two objectives meet. A major impacting factor is the efficiency of the PI-hub in handling goods. Future work includes enhancing the model for consideration of constraints related to a more detailed load planning to consider the dimensions of modular containers and modeling the internal PI-hub operations and mirroring its impact on network operations.

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