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Multi-objective Truck Scheduling in a Physical Internet Road-Road Cross-docking Hub

Tarik Chargui * **Abdelghani Bekrar** * **Mohamed Reghioui** ** **Damien Trentesaux** *

* *LAMIH, UMR CNRS 8201, Université Polytechnique Hauts-de-France, Le Mont Houy, 59313, Valenciennes, France (e-mail: tarik.chargui@gmail.com, {abdelghani.bekrar, damien.trentesaux}@uphf.fr).*
** *MOSIL Laboratory, National School of Applied Sciences of Tetouan, University of Abdelmalek Essaadi, Tetouan, Morocco (e-mail: m.reghioui@gmail.com)*

Abstract: Aiming towards a sustainable supply chain, Physical Internet (PI) has been presented as a global logistics network with standardized PI-containers. PI-nodes, and more specifically PI-hubs, are one of the key elements of the Physical Internet concept. This paper focuses on optimising operations in the Road-Road PI-hub, which was not addressed in the Physical Internet literature. Road-Road PI-hubs are designed to transfer PI-containers between suppliers' and customers' trucks. The objective is to minimize both the inbound/outbound trucks delays and the energy consumption during the transferring of PI-containers using PI-conveyors. The problem is formulated as a multi-objective mixed integer model (MO-MIP) to find the optimal Pareto front. The mathematical model is tested on an illustrative instance to show the trade-off between trucks' delays and PI-containers routing energy consumption. The primary goal of this paper is to provide a prospect to start optimizing PI-hubs by suggesting a multi-objective mathematical model as a beginning for future researches on the Road-Road PI-hubs.

Keywords: Logistics, Cross-docking, Physical Internet, Road-Road PI-hub, Truck scheduling, Mathematical programming, Multi-objective optimization, Optimal Pareto front.

1. INTRODUCTION

In the global supply chain, cross-docking is an efficient facility for transferring products between suppliers and customers from inbound to outbound vehicles such as trucks, trains, ships, etc, (Theophilus et al., 2019; Ladier and Alpan, 2016; Van Belle et al., 2012). Distributing products in an efficient and also sustainable way is becoming a challenge for many logistics and transportation companies. In this context, Physical Internet (PI) has been presented as a possible solution among many other ambitious concepts (Internet of Things (Witkowski, 2017; Liu et al., 2019), Industry 4.0 (Facchini et al., 2020; Tang and Veelenturf, 2019; Kostrzewski et al., 2020), etc). Physical Internet aims to create a global logistics network in which the storage and transportation resources are shared between suppliers, distribution centres, and clients. PI is based on the idea of encapsulating products in smart PI-containers which are designed to be interconnected and easy to handle and store. This logistics network is designed to be economically, environmentally, and socially sustainable (Montreuil et al., 2013a; Zhong et al., 2017).

Physical Internet is composed of three key elements: PI-containers, PI-movers and PI-nodes (Montreuil et al., 2013b). PI-containers are smart sustainable containers with standardized dimensions. PI-movers are used to move the PI-containers through the Physical Internet (PI-locomotives, PI-trucks, etc). Finally, PI-nodes are transit centres to transfer PI-containers between different types of vehicles:

- **Road→Rail PI-hubs:** This category of PI-hubs is used to transfer PI-containers from the incoming trucks to the outgoing trains (Ballot et al., 2012; Chargui et al., 2019b).
- **Rail→Road PI-hubs:** Their main function is to move PI-containers in the opposite direction of the Road-Rail PI-hub, from the inbound trains to the outbound trucks (Vo et al., 2018; Chargui et al., 2019a; Walha et al., 2016).
- **Rail↔Road PI-hubs:** Move the PI-containers in both directions between trains and trucks (Chargui et al., 2019c).
- **Water↔Road PI-hubs:** Manage the transfer of PI-containers between ships and trucks (Montreuil et al., 2013b).
- **Road↔Road PI-hubs:** Those PI-hubs handle the transferring of PI-containers between inbound and outbound trucks (Meller et al., 2012; Chargui et al., 2019d).

This paper focuses on the last type of PI-hubs. The Road-Road PI-hubs have not been studied yet from a multi-

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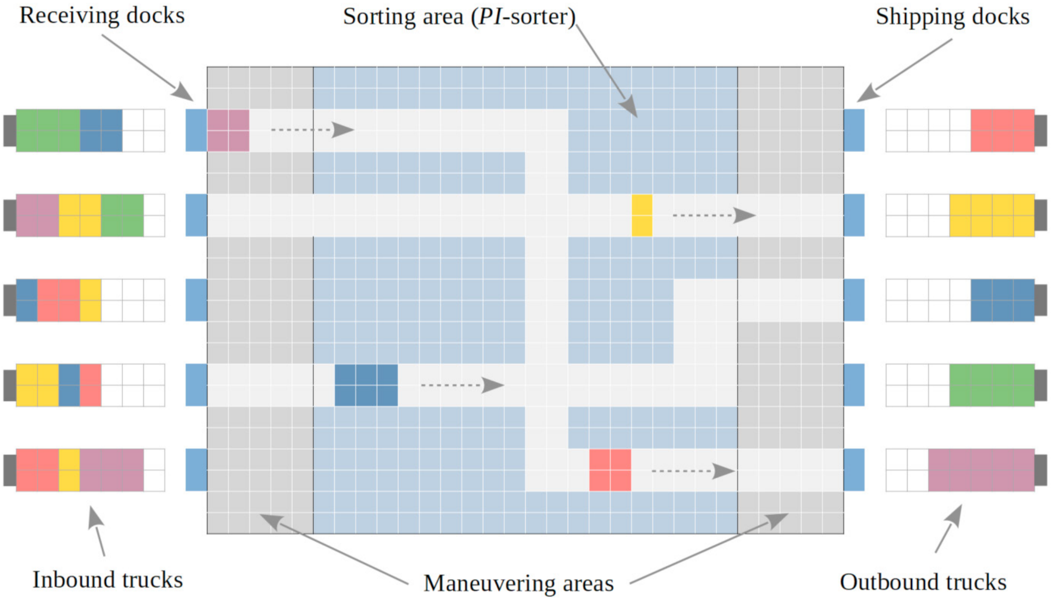

Fig. 1. Functional design of the Road-Road PI-hub

objective perspective. The objective of this paper is to mathematically formulate and solve the truck scheduling and PI-containers routing as a multi-objective mixed integer mathematical model (MO-MIP). The objective is to find the optimal Pareto front by minimizing both the trucks delays and the energy used for the routing of PI-containers between inbound and outbound trucks.

The remaining of this paper is structured as follows: Section 2 presents the functional design of the studied Road-Road PI-hub and the literature of the cross-docking hubs in the Physical Internet context. The proposed multi-objective mathematical model is presented in Section 3. Section 4 analyses the experimental results. Finally, Section 5 concludes the work with several future directions.

2. LITERATURE REVIEW

This section presents the functional design of the Road-Road cross-docking PI-hub, followed by a review on the literature of cross-docking problems in the Physical Internet context.

2.1 Functional design of the Road-Road PI-hub

In the Physical Internet context, Road-Road PI-hubs are designed to transfer PI-containers from suppliers' incoming trucks to customers' outgoing trucks through a sorting area as illustrated in Fig. 1. In the first step, PI-containers are automatically unloaded from the inbound trucks at the PI-docks and then routed to the manoeuvring area for shipping at the outbound docks. In the sorting area (PI-sorter), the PI-containers slide on the PI-conveyors units until they arrive at the shipping side. The inbound and outbound trucks arrive at a specific time and are preferred to leave at a specific departure time. The objective is to minimize the trucks tardiness as well as the energy used to move the PI-containers in the PI-sorter zone. The problem is formulated mathematically in section 3.

2.2 Related works in the Physical Internet context

The recent researches on Physical Internet are more focused on the optimization of the global supply chain process (Rodríguez Cornejo et al., 2020; Pan et al., 2019). For instance, Peng et al. (2020) formulated mathematically the integrated production inventory distribution network to evaluate the sustainability performance in Physical Internet. The results confirm the ability of the PI to improve the sustainability while increasing the vehicles utilization. Dynamic and integer programming can also be coupled to solve less-than-truckload carriers in the Physical Internet (Qiao et al., 2020). Other studies, such as in Gumzej et al. (2020), focus on designing intelligent transport unit for the air transport in Physical Internet. Other researches such as in Kantasa-ard et al. (2020) address the PI logistics network from a machine learning perspective for demand forecasting. The performance of their approach was then evaluated on a real case study. All the researches above focus on the whole supply chain process.

PI-nodes, and more specifically PI-hubs, have been addressed with different approaches in recent years. Rail-Road PI-hubs were widely addressed in the Physical Internet literature especially from a multi-agent simulation prospect by developing control architectures using multi-agent systems for PI-containers routing (Vo et al., 2018; Chargui et al., 2019b; Pach et al., 2014) or to optimize the assignment of trucks and the grouping of PI-containers (Walha et al., 2016; Chargui et al., 2018). Other researches coupled simulation with optimization to generate robust solutions for Road-Road PI-hubs (Chargui et al., 2019d) and the two-way Road-Rail PI-hubs (Chargui et al., 2019c).

Multi-objective approaches are becoming more common in the cross-docking literature (Theophilus et al., 2019). However, most of the previous studies on PI-hubs either use a given lexicographic order for the objective functions (Chargui et al., 2019a) or a weighted sum for prioritizing objectives (Chargui et al., 2019b; Walha et al., 2016).

Since optimization studies on Road-Road PI-hubs have not been addressed yet, this paper proposes a multi-objective mathematical programming model (MO-MIP) to determine the optimal Pareto front for the trade-off between the trucks tardiness and energy consumption of the routing of PI-containers. The next section (Section 3) provides the notations for the parameters, decision variables, the normalized weighted sum of the objective functions, and the constraints.

3. MATHEMATICAL FORMULATION

This section presents the mathematical formulation of the problem as a multi-objective mixed integer programming model (MO-MIP).

3.1 Input data and parameters

N^I	Number of inbound trucks
N^O	Number of outbound trucks
M^I	Number of inbound docks
M^O	Number of outbound docks
N^C	Total number of PI-containers
P_k^I	Position of receiving dock k
P_l^O	Position of shipping dock l
Y	Number of PI-conveyors from receiving side to shipping side
A_i^I	Arrival time of inbound truck i
D_i^I	Preferred departure time of inbound truck i
A_j^O	Arrival time of outbound truck j
D_j^O	Preferred departure time of outbound truck j
L_c^C	Length of PI-container c ($\times 1.2m$)
G_{ij}	Binary PI-containers flow matrix between inbound and outbound trucks ($G_{ij} = 1$ if there is at least one PI-container moving from inbound truck i to outbound truck j, 0 otherwise)
B_{ic}^I	= 1 if inbound truck i contains PI-container c, 0 otherwise
B_{jc}^O	= 1 if PI-container c will be shipped into outbound truck j, 0 otherwise
U	Time to load/unload one PI-container from trucks
T	Number of time units to move a PI-container from a PI-conveyor unit to another
E	Trucks changeover time
C^E	Energy cost for one PI-conveyor move
M	A big positive number

3.2 Decision variables

s_i^I	Unloading start time of inbound truck i
e_i^I	Unloading end time of inbound truck i
s_j^O	Loading start time of outbound truck j
e_j^O	Loading end time of outbound truck j
σ_c	Number of PI-conveyors used to move PI-container c from inbound dock to outbound dock
x_{ik}	= 1 if inbound truck i is assigned to receiving dock k, 0 otherwise
y_{kl}	= 1 if outbound truck j is assigned to shipping dock l, 0 otherwise
p_{im}	= 1 if inbound truck i is unloaded before inbound truck m, 0 otherwise
q_{jn}	= 1 if outbound truck j is loaded before outbound truck n, 0 otherwise
h_{ijkl}	= 1 if inbound truck i is assigned to receiving dock k and outbound truck j is assigned to shipping dock m while $G_{ij} = 1$, 0 otherwise
α	Weighting factor for F^T and F^E ($\alpha \in [0, 1]$)
I_{F^T}	The optimal value for F^T while $\alpha = 1$
I_{F^E}	The optimal value for F^E while $\alpha = 0$
N_{F^T}	The best value of F^T corresponding to the optimal value of F^E
N_{F^E}	The best value of F^E corresponding to the optimal value of F^T

3.3 Objective function: Normalized weighted sum

There are two objective functions in this model, the first one is the inbound and outbound trucks tardiness F^T, the second objective is the total energy consumed by the PI-conveyors in the sorting area F^E. Since the two objectives have different measuring units (time units for F^T and energy cost for F^E), it necessary to normalize both objectives. In this case, we use the Nadir and Ideal points as used in Demir et al. (2014). The Ideal point (I_{F^T}, I_{F^E}) presents the best possible values of both F^T and F^E. In Nadir point (N_{F^T}, N_{F^E}), N_{F^T} is the best value of F^T corresponding to the optimal value of F^E, and N_{F^E} is the best value of F^E when F^T is at its optimal value. The obtained formulation is presented in Equation 1.

Minimize: $\alpha F^T + (1 - \alpha) F^E$

Where:

$$F^T = \frac{\sum_{i=1}^{N_I} (e_i^I - D_i^I) + \sum_{j=1}^{N_O} (e_j^O - D_j^O) - I_{F^T}}{N_{F^T} - I_{F^T}}$$

$$F^E = \frac{\left(\sum_{h=1}^{H} C_i^E \sigma_c \right) - I_{F^E}}{N_{F^E} - I_{F^E}} \tag{1}$$

3.4 Trucks assignment constraints

Equations 2 and 3 ensure that each inbound/outbound truck is handled by one dock.

$$\sum_{k=1}^{M^I} x_{ik} = 1 \qquad (\forall i = 1 ... N^I) \tag{2}$$

$$\sum_{l=1}^{M^O} y_{jl} = 1 \qquad (\forall j = 1 ... N^O) \tag{3}$$

Equations 4 - 6 calculate the value of h_{ijkl} using the trucks assignment x_{ik} and x_{jl} and the flow matrix G_{ij}

$$\sum_{k=1}^{M^I} \sum_{l=1}^{M^O} h_{ijkl} = G_{ij} \qquad (\forall i = 1 ... N^I, \forall j = 1 ... N^O) \tag{4}$$

$$h_{ijkl} \leq x_{ik} \quad (\forall i = 1 ... N^I, \forall j = 1 ... N^O, \forall k = 1 ... M^I, \forall l = 1 ... M^O) \tag{5}$$

$$h_{ijkl} \leq y_{jl} \quad (\forall i = 1 ... N^I, \forall j = 1 ... N^O, \forall k = 1 ... M^I, \forall l = 1 ... M^O) \tag{6}$$

Equations 7 - 10 handle the sequencing of the inbound/outbound trucks if they are assigned to the same receiving/shipping dock. Equations 7 and 8 ensure that an inbound/outbound truck does not precede itself ($p_{mm} = 0$ or $p_{nn} = 0$). Equations 9 and 10 calculate the values of p_{im} and p_{jn} using the assignment variables x_{ik} and y_{jl}.

$$p_{im} + p_{mi} \leq 1 \quad (\forall i, m = 1...N^I) \tag{7}$$

$$q_{jn} + q_{nj} \leq 1 \quad (\forall j, n = 1...N^O) \tag{8}$$

$$\begin{aligned} &x_{ik} + x_{mk} - 1 \leq p_{im} + p_{mi} \\ &\quad (\forall i, m = 1...N^I, \forall k = 1...M^I : i \neq m) \end{aligned} \tag{9}$$

$$\begin{aligned} &y_{jl} + y_{nl} - 1 \leq q_{jn} + q_{nj} \\ &\quad (\forall j, n = 1...N^O, \forall l = 1...M^O : j \neq n) \end{aligned} \tag{10}$$

3.5 Truck scheduling constraints

Equation 11 guarantees that each inbound truck starts unloading after arriving at the dock. The starting and ending time of unloading inbound trucks is calculated using Equations 12 - 13.

$$s_i^I \geq A_i^I \quad (\forall i = 1...N^I) \tag{11}$$

$$s_m^I \geq e_i^I + E - M(1 - p_{im}) \quad (\forall i, m = 1...N^I) \tag{12}$$

$$e_i^I \geq s_i^I + U \sum_{c=1}^{N^C} B_{ic}^I \quad (\forall i = 1...N^I) \tag{13}$$

Equation 14 ensures that all the outbound trucks start loading PI-containers after their arrival at the docks. Equations 15 - 17 calculate the start/end time of loading outgoing trucks while considering both the loading time (Equation 16) and the transfer time from inbound to outbound docks (Equation 17).

$$s_j^O \geq A_j^O \quad (\forall j = 1...N^O) \tag{14}$$

$$s_n^O \geq e_j^O + E - M(1 - q_{jn}) \quad (\forall j, n = 1...N^O) \tag{15}$$

$$e_j^O \geq s_j^O + U \sum_{c=1}^{N^C} B_{jc}^O \quad (\forall j = 1...N^O) \tag{16}$$

$$\begin{aligned} e_j^O \geq\ & s_j^O + U \sum_{c=1}^{N^C} B_{jc}^O + T(|P_k^I - P_l^O| + Y) \\ & -M(1 - h_{ijkl}) \quad (\forall i = 1...N^I, \forall j = 1...N^O, \\ & \forall k = 1...M^I, \forall l = 1...M^O) \end{aligned} \tag{17}$$

3.6 PI-conveyors utilization

Equation 18 calculates the number of conveyors used for transferring each PI-container c from receiving docks to shipping docks.

$$\begin{aligned} \sigma_c \geq\ & L_c^C |P_k^I - P_l^O| + 2Y - M(3 - (B_{ic}^I + B_{jc}^O + h_{ijkl})) \\ & (\forall c = 1...N^C, \forall i = 1...N^I, \forall j = 1...N^O, \\ & \forall k = 1...M^I, \forall l = 1...M^O) \end{aligned} \tag{18}$$

Equations 19 and 20 ensure that the variables are respectively positive or binary.

$$\begin{aligned} & s_i^I, e_i^I,\ s_j^O, e_j^O, \sigma_c, \alpha, I_{F^T}, I_{F^E}, N_{F^T}, N_{F^E} \geq 0 \\ &\quad (\forall c = 1...N^C, \forall i = 1...N^I, \forall j = 1...N^O, \\ &\quad \forall k = 1...M^I, \forall l = 1...M^O) \end{aligned} \tag{19}$$

$$\begin{aligned} & x_{ik}, y_{jk},\ p_{im}, q_{jn}, h_{ijkl} \\ &\quad (\forall i, m = 1...N^I, \forall j, n = 1...N^O, \\ &\quad \forall k = 1...M^I, \forall l = 1...M^O) \end{aligned} \tag{20}$$

4. A NUMERICAL EXAMPLE

In order to illustrate the trade-off between the two objectives (F^T and F^E), the proposed mathematical model (MO-MIP) is tested on a random illustrative instance. The model is developed on IBM CPLEX solver (version 12.9). The test is performed on a 2.5 GHz laptop with 4 GB of RAM. The values of the parameters used in the instance are summarized in Table 1.

Table 1. Values of parameters in the instance

Parameters	Values	Parameters	Values
$N^I + N^O$	8 + 8	G_j^i, B^I, B^O	Binary matrix
$M^I + M^O$	5 + 5	L_i^C	[2,5]
N^C	24	U	10
A_i^I	[12,124]	T	2
D_i^I	[32,144]	E	5
A_j^O	[33,160]	Y	30
D_j^O	[53,180]	C^E	1.2

The obtained results are presented in Table 2. The first column shows the value of α from 0.0 to 1.0 with a step of 0.1. The second and third columns present the tardiness of inbound and outbound trucks respectively. Columns 4 and 5 show the values of both objective function F^T and F^E. The last column provides the computational time in seconds.

Table 2. Detailed results for $0 \leq \alpha \leq 1$

α	F^T (Inb.)	F^T (Outb.)	F^T	F^E	Time (s)
0.0	511	1597	2108	1728	4.24
0.1	511	1597	2108	1728	172.69
0.2	282	1035	1317	1747.2	566.8
0.3	282	1035	1317	1747.2	114.44
0.4	282	1035	1317	1747.2	68.11
0.5	168	844	1012	1776	86.86
0.6	168	844	1012	1776	153.13
0.7	97	798	895	1795.2	90.34
0.8	89	703	792	1824	89.45
0.9	80	688	768	1843.2	63.31
1.0	80	661	741	1872	8.62
Average	231.81	985.18	1217	1780.36	128.91

Those results are illustrated in Fig. 3. As it can be noticed for the two objective functions F^T and F^E, when trucks' tardiness decreases, the energy consumption slightly increases. Fig. 2 shows the optimal Pareto front obtained for both objectives. The coefficient α remains a tuning parameter that can be set by the PI-hub manager depending on the priorities of the hub facility.

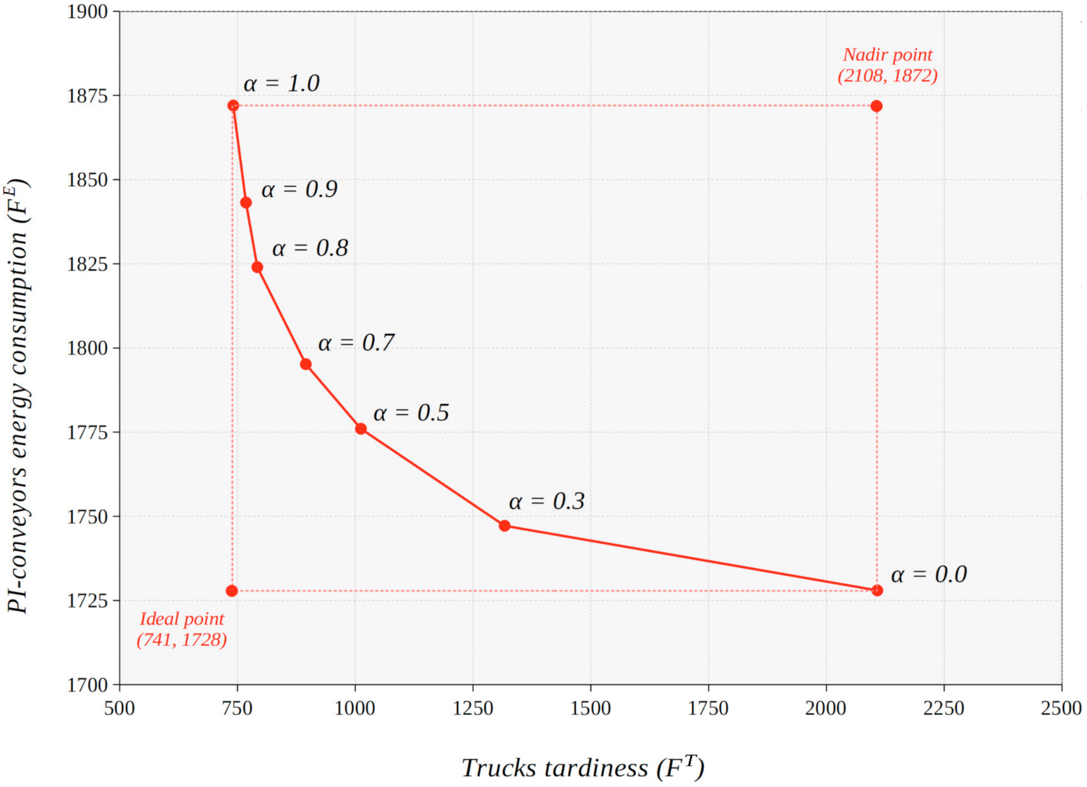

Fig. 2. The optimal Pareto front for F^T and F^E

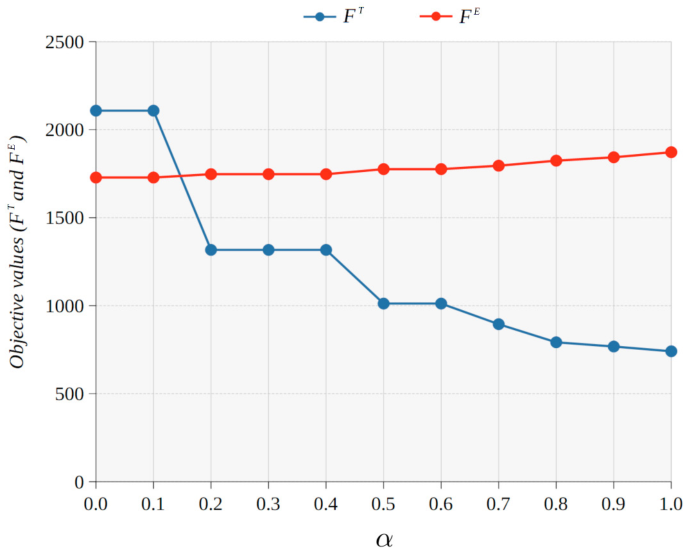

Fig. 3. Objective functions (F^T and F^E) for $\alpha \in [0, 1]$

5. CONCLUSION

The main objective in this research was to study the Road-Road Physical Internet hub which has not been addressed in the literature especially from a multi-objective perspective. This paper focused the truck scheduling and PI-containers routing in a Road-Road PI-hub. A multi-objective mixed integer programming model was proposed and solved to find the optimal Pareto front. The objective was to minimize the inbound and outbound trucks tardiness in addition to the PI-conveyors energy consumption when transferring PI-containers.

Through this research, the authors wish to give the opportunity to start new researches on Road-Rail PI-hubs optimization by formulating the problem mathematically from a multi-objective perspective. As a future direction of this work, it would be interesting to develop other solution methods such as meta-heuristics that can be incorporated into decision support tools to help the PI-hub managers in their daily operational tasks. Another important opportunity for future research is to consider the possible disruptions on receiving and shipping docks or in the PI-conveying system or unexpected truck delays. To deal with such disruptions, there are various approaches that can be developed, such as simulation-optimization by incorporating a simulator into the meta-heuristic to generate robust solutions or multi-agent simulation to generate alternative solutions in real time.

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