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Towards designing and operating Physical Internet cross-docks: problem specifications and research perspectives

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Abstract

Cross-docking is a common logistics practice applied in transit platforms to synchronize inbound and outbound vehicles in order to avoid keeping in-between storage. The practice plays a critical role to accelerate transportation flows. In this paper, we focus on Physical Internet (PI or π -) cross-docks and discuss how this concept changes the current classical design, management and optimization of cross-docking platforms. We present the optimization problems related to cross-docks in the PI context and highlight the distinctive features of a π -cross-dock. A review of the existing literature on the main ideas and components of the π -concept, and on the design and operations of π -cross-docks (π -hubs) is firstly presented. Then, the functional design of the π -cross-dock and the classical one are discussed while highlighting the distinctive features of both configurations. The different cross-docking optimization problems arising from the PI paradigm are then specified at the strategic, tactical and operational decision levels, showing how they differ from the problems already addressed for “traditional” cross-docking platforms. Finally, as a proof of concept, a preliminary study is carried out on one of the newly specified problems.

Keywords: Logistics, Cross-docking design, Cross-docking operations, Physical Internet, Multi-modal transportation, Mathematical Programming

1. Introduction

1.1. The PI concept and the key components

Many concepts and paradigms have been suggested in the literature to design global supply chains. Among the most studied concepts, particular research interests have been focused on Physical Internet, Industry 4.0, or Internet of Things. Especially, Physical Internet (hereafter PI or π) has been introduced by Montreuil (2011) and Montreuil et al. (2013a) as an ambitious vision and a paradigm shift aiming at transforming the way physical objects are moved, stored, supplied and used, inspired from the way computers are interconnected through the (digital) Internet. The goal is to entirely reorganize the distribution of goods in an efficient way which is economically, environmentally and socially sustainable. This vision is defined through thirteen characteristics in (Montreuil, 2011). Those characteristics, to be further detailed in coming sections, are grouped in three main sub categories: the encapsulation of products and materials in standardized containers called π -containers, the automation of the handling process by using automated conveying and storage systems, and the universal interconnectivity using intermodal transportation. The interested reader can refer to (Montreuil, 2011) for further description.

Focusing on the impact of the PI paradigm shift on logistic facilities and material handling, [Montreuil et al. \(2010\)](#) name and define the three key components of PI that are necessary to ensure its proper functioning : π -movers move π -containers between π -nodes (Figure 1). π -containers are standardized containers, that can be managed and stored by different companies. π -movers are used to move and manipulate π -containers such as π -vehicles (π -trucks, π -lift, etc.) and π -carriers (π -wagons, π -trailers, etc.). π -nodes are locations for receiving, storing and transferring π -containers between π -movers ; they can be π -transits, π -switches, π -bridges or π -hubs, such as Road-rail π -hubs and road-road π -hubs ([Montreuil et al., 2013a](#); [Sarraj et al., 2014b](#)). For a systemic definition of the PI system and components, we refer to the book and the review [Ballot et al. \(2014\)](#); [Ambra et al. \(2019\)](#).

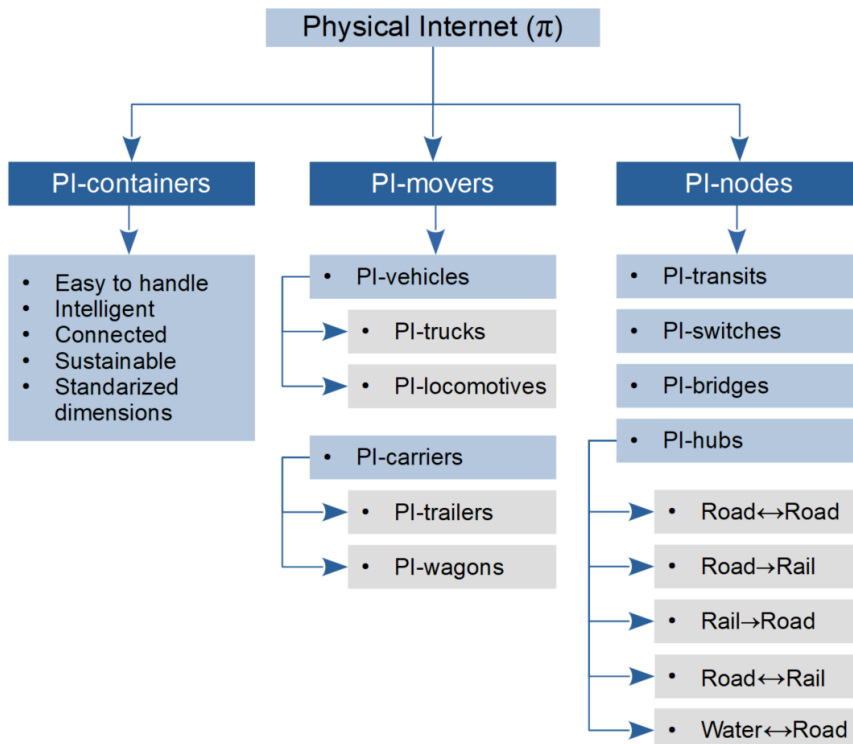


Figure 1: Physical Internet main components

Current logistics operations consist largely in moving pallets around, yet stackable, interlockable π -container may remove the need for pallets ([Landschützer et al., 2015](#)). As a result, a complete redesign of the material handling systems, including π -lift-trucks, π -conveyors, π -trucks, etc., is needed in the new paradigm. The same goes for the π -nodes, that are to be redesigned or reinvented.

1.2. π -nodes as the backbone

We focus here on a particular type of π -nodes, called π -hubs by [Montreuil et al. \(2010\)](#):

“The π -hubs are π -nodes having for mission to enable the transfer of π -containers from incoming π -movers to outgoing π -movers. Their mission is conceptually similar to the mission of π -transits, but dealing with π -containers themselves rather than dealing strictly with the π -carriers. They enable unimodal π -container cross-docking operations.” ([Montreuil et al., 2010](#))

Developing new generations of logistics nodes towards PI-hubs is one of the strategic axes in the new roadmap for PI development and implementation at Europe level, published in 2020

by the European Technology Platform ALICE¹ (ALICE-Roadmap, 2021). According to the roadmap and the recommendations, conventional logistics nodes (including inland hubs and terminals) should be fully automated by 2030, and interconnected to become autonomous π -nodes by 2040. This step is critical to PI implementation since it facilitates the accessibility and usability of the services at network level, especially for multi- or synchro-modal transportation that is strongly relying on terminals or transshipment hubs and the real-time information of sites and flows. The objective leads to an urgent call for more research on π -hub automation and automated scheduling design. This paper contributes to this research stream, also recently linked to the concept of synchromodality (Giusti et al., 2019; Ambra et al., 2019) and pays special attention to energy consumption problem to investigate the sustainability issues in the process of automation.

A three-paper series (Ballot et al., 2012a; Meller et al., 2012; Montreuil et al., 2012) proposes key performance indicators and functional designs for PI facilities, specifically a road-rail π -hub (Ballot et al., 2012a) and a road-based π -hub (Montreuil et al., 2012). Both facilities process π -containers of fixed section but with various lengths. The road-rail π -hub (Ballot et al., 2012a) transfers them between a train (whose railcars are never detached) and several trucks, using π -bridges to rotate the π -containers when needed, and π -sorters to act as temporary buffers and sort the π -containers between the two connecting services. The road-road π -hub (Montreuil et al., 2012) unloads the π -containers from their inbound truck and consolidates them to reload the outbound trucks. The consolidation process is achieved through a flexible network of π -sorters used in combination with π -buffers (as opposed to Ballot et al. (2012a) where π -sorters are also temporary buffers), never rotating the π -containers.

Based on such modes of operations, π -hubs issues appear strongly related to cross-docking design and operations, especially for multi-modal transportation. Although only Montreuil et al. (2012) use explicitly the term “cross-docking” (and “ π -cross-dock” as a synonym for π -hub facility), both the road-rail and the road-road π -hubs are cross-docking facilities as defined by the Council of Supply Chain Management Professionals in their glossary (CSCMP, 2013):

“*Cross-docking*: distribution system in which merchandise received at the warehouse or distribution center is not put away, but instead is readied for shipment to retail stores. Cross-docking requires close synchronization of all inbound and outbound shipment movements. By eliminating the put-away, storage and selection operations, it can significantly reduce distribution costs”. (CSCMP, 2013)

Although the term π -hub fits better with the Internet metaphor and incorporates a multi-modal dimension, in this article we prefer its counterpart π -cross-dock, because it is more familiar to supply chain professionals. Thanks to the high level of standardization and automation, there are not many fundamental differences between operating a road-road π -hub, a rail-road π -hub or a water-road π -hub (except of course the environmental footprint of the operations and the dynamics of the transportation systems). While traditional road-road cross-docking operations have been mostly considered separately from rail-road operations so far, in the PI paradigm, operations management is similar enough to consider all multi-modal π -cross-docking operations together (as done by Boysen et al. (2015) in a different context). We focus on π -cross-docks connected to on-land transportation modes, i.e. rail, road and water only. π -hubs connected to sea and air transport modes are out of scope for our study, because their operations vary significantly from those of rail/road/water π -cross-docks.

¹Alliance for Logistics Innovation through Collaboration in Europe

The articles introducing the rail-road and the road-road π -hubs (Ballot et al., 2012a; Montreuil et al., 2012) present conceptual designs as proof of concept, without providing mathematical models for optimal design or operation management. The layout design and sizing are done through trial-and-error using discrete-event simulation. Only a few articles in the literature deal with π -cross-dock related problems ; they use mostly multi-agent simulation or local search heuristics (Furtado et al., 2013; Pach et al., 2014a,b; Walha et al., 2014; Sallez et al., 2015a; Pawlewski, 2015; Chargui et al., 2019, 2020). The question of how to manage and operate these highly automated facilities in a smooth, optimized way has never been adequately addressed according to Sallez et al. (2015a). Besides, the issue of composing modular containers to fit the length of a truck is often simplified as "to be put side by side" (Montreuil et al., 2012) whereas it is actually a bin packing problem, known as NP-hard problem (Garey & Johnson, 1979). This state-of-the-art is in stark contrast with the rich literature in "classical" cross-docking operations (Boysen & Fliedner, 2010; Van Belle et al., 2012; Buijs et al., 2014; Ladier & Alpan, 2015), that successfully use mathematical optimization to design, manage and operate cross-docking. It thus appears that the numerous mathematical optimization problems that could help designing, managing and operating π -cross-docks are still to be defined and specified.

Besides, the COVID pandemic has also stressed the importance of multi-modal transportation relying on fast and efficient transit hubs, especially for the Trans-European Transport Network (TEN-T). The urgency of transforming traditional cross-docking centers into more automated and efficient ones is therefore obvious. Recent works showed that Physical Internet aspects can solve COVID related supply chain disruptions (Safwen & Németh, 2021).

1.3. The contributions of this work

The goal of this article is therefore to specify and present in a structured way the different cross-docking optimization problems arising from the PI paradigm, and to show how they differ from the problems already addressed for "traditional" cross-docking platforms. From this assessment, numerous research perspectives are defined, in the hope that they will be tackled by the operations research community in order to facilitate a future implementation of the PI vision. More specifically, the contributions of this paper are twofold : 1) to present the most distinctive features of π -cross-docks comparing with the classic mode ; and 2) to specify the optimization problems that are specific to π -cross-dock at strategic, tactical, and operational decision levels. As a first proof of concept, we carry out a preliminary study on one of the newly specified problems, comparing a classical and a π -cross-dock on a toy instance.

From a practical point of view, the importance of efficient and sustainable PI-hubs has been evidenced in several projects especially in Europe, for example, SYNCHRO-NET (2021) aims at advancing synchro-modal transportation relying on efficient multi-modal hubs, and SuperGreen (2021) focuses on developing Green Corridors using new and green cargo handling technologies at logistics hubs and terminals.

The remainder of this article is structured as follows. First, section 2 presents in more details the existing literature regarding cross-dock facilities, in order to highlight the distinctive features of a π -cross-dock compared to a traditional one, and to map the existing optimization work in π -cross-dock. Next, following a framework inspired by those proposed in several reviews of cross-docking optimization problems (Boysen & Fliedner, 2010; Van Belle et al., 2012; Buijs et al., 2014; Ladier & Alpan, 2015), a list of novel π -cross-dock optimization problems is established and commented for strategic, tactical (section 3), and operational (section 4) decision levels. Then, in section 6 presents two multi-objective mathematical models for the classical and π -cross-dock. Conclusive remarks and research perspectives are finally presented in section 7.

2. From cross-docks to π -cross-docks

2.1. Distinctive features of a π -cross-dock

This section studies the distinctive features of π -cross-docks and their functional differences with traditional cross-docks.

2.1.1. Distinctive nature and design issues of PI-cross-dock centers

From the functional description of a road-road cross-docking hub proposed by [Montreuil et al. \(2012\)](#), one can infer a set of specifications that make a π -cross-dock distinctively different from its traditional counterpart. From our point of view, there are four main global specifications that make a π -cross-dock fundamentally different from a classical cross-dock. They are here introduced and will serve as a basis to make the relevant optimization problems explicit in the following sections.

Firstly, products transiting through a π -cross-dock can belong to any π -certified user, not just a single company or a restricted set of clients. The PI network is designed to avoid redundancies and improve consolidation, with π -hubs located close enough from one another for truck drivers to be able to go home every night. The pool of origins and destinations served by a π -cross-dock is therefore more restricted than in a traditional cross-dock, while the quantity processed are probably larger.

Secondly, a π -cross-dock does not handle various kind of logistics units, e.g. pallets, cases or other SKUs;² it handles only modular, standardized π -containers. Since π -containers can be composed recursively by smaller π -containers or can be assembled with other π -containers, the π -cross-dock operations can include de-aggregation into smaller π -containers or consolidation into larger π -containers. Each π -container carries its own information (origin, destination, owner, delivery time window), and as such has, to a certain extent, a capacity to make decisions (see [Sallez et al. \(2015b\)](#)). Ideally, π -containers can be loaded and unloaded from the top, rear, left and right of trucks (even the front if the trailer is unhooked). They are set down directly on the π -vehicle (truck, train, barge) without extra covers or closed walls. Therefore, when loading a vehicle by interlocking smaller π -containers, it is important to avoid holes, in order to maintain the structural integrity of the composition ([Montreuil et al., 2010](#)) and to avoid transporting empty space. Given enough π -containers, creating a perfect parallelepiped should be feasible thanks to their standardized sizes.

Thirdly, to operate smoothly, π -cross-docks work on a mostly automated environment, using innovative handling systems instead of classical conveyors. For example, π -containers could route themselves automatically through a 2-dimensional grid of π -conveyors – each conveyor being able to carry a container in four directions. Lifting containers could be done using their snapping capability instead of forks. Compared to traditional man-handled cross-docking operations, the π -cross-dock implies shorter loading/unloading times and opens new internal routing challenges.

Examples of road-water and road-road π -cross-docks are proposed by [Montreuil et al. \(2010, 2012\)](#), see [Figure 2](#).

2.1.2. Critical operations and decisions in PI-cross-dock centers

The distinctive features described in the previous section enlighten several key differences between traditional cross-docks and their PI counterparts. Hence, several key decision problems identified by [Buijs et al. \(2014\)](#) are not relevant for π -cross-docks:

²SKU: Stock Keeping Unit

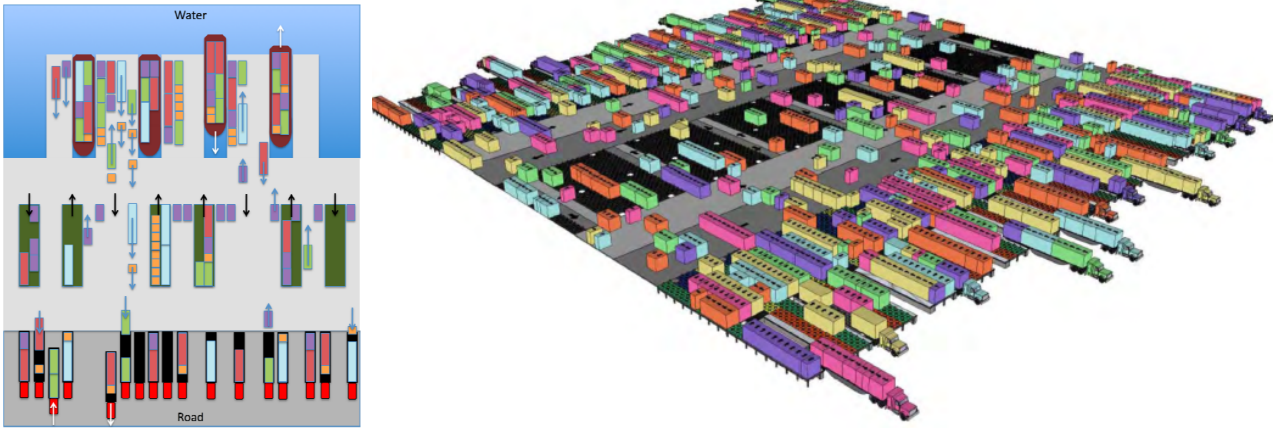


Figure 2: Illustrative water-road and road-road π -hubs (sources: Montreuil et al. (2010, 2012))

Level of automation. Although the choice for the level of automation is an important decision in a traditional cross-dock (especially to assess the trade-off between automation and flexibility), the PI paradigm assumes a very high level of automation. The design of the suitable handling equipment is still an open research question, with a larger scope than for the π -cross-dock since it impacts the entire PI network. Therefore, we consider that this question is out of scope of our study.

Equipment capacity planning. Clearly, the open research question of designing handling equipment for a π -cross-dock must be resolved, before the question of their capacity planning can be addressed from an operations research point of view.

Internal transportation technology. The internal resources that are used to move containers inside a cross-dock plays a critical role in the efficiency of the platform. Automation has an important role in increasing productivity and flexibility while providing safety to the workplace compared to traditional resources such as forklifts (Zsifkovits et al., 2020).

Workforce capacity planning/scheduling. Because π -cross-docks are meant to be very highly automated, all decision problems regarding the workforce are nearly not relevant. While workforce capacity planning or workforce scheduling problems are of crucial importance in classical cross-docks (as shown in Ladier & Alpan (2015)), they do not need to be considered in this context.

Temporary storage. In traditional cross-docking facilities, items are meant to be transferred in less than 24 hours; because a π -container is likely to go through several π -cross-docks between its origin and its destination, this maximum leadtime should obviously be greatly reduced in the PI. One way to achieve shorter leadtimes is to remove temporary storage entirely. So far in the cross-docking literature and practice (Ladier & Alpan, 2015), temporary storage is usually forbidden if storage space is highly constrained or for sanitary reasons (frozen food, drugs); in other cases items can sit aside while waiting for their vehicle to arrive. Because this should be avoided to accelerate the flow of goods, we believe there should not be a dedicated staging area in a π -cross-dock, thus the related design problems are irrelevant. Because temporary storage can never be removed entirely, π -containers can stand still on their π -sorters (or π -buffers, see Montreuil et al. (2012)) for short periods of time if needed.

Another important difference is the set of performance measures, or objective functions used to evaluate the quality of a decision. [Ladier & Alpan \(2015\)](#) analyze the cross-docking literature from 1990 to 2014 to identify the most commonly used objective functions when optimizing cross-docking operations. They obtain, by decreasing order, the completion time or makespan (45%), the distance traveled by the employees (usually assumed to be proportional to the labor cost) (26%), the deviation compared to the planned truck processing time (17%), the inventory level (12%). All other performance measures appear in less than 7% of the considered articles. The authors suggest that congestion-related performance measures should be more widely used in order to match the cross-dock managers' needs.

[Ladier & Alpan \(2015\)](#) show that the makespan, although a very popular performance measure inherited from production scheduling, is not a very relevant one for cross-dock practitioners: indeed, the last operation of the day is usually constrained by the departure time of the last truck, which is not necessarily flexible. The same applies for π -cross-docks; besides, π -facilities operate round the clock, and the makespan is not a very suitable objective function when scheduling over a rolling horizon. The makespan embodies the idea that overall the operations should end as soon as possible; in the PI paradigm, each π -container should be processed as soon as possible. Objective functions related to the π -containers individual leadtimes (maximum, average...) should therefore be preferred to the makespan to make decisions for π -cross-docks.

In tactical cross-dock facility related problems, [Buijs et al. \(2014\)](#) also note that “a typical objective used by cross-dock managers is to minimize the material handling effort required” to transfer the products. But due to the high level of automation, the effort or labor cost is not a relevant objective function any more in the PI paradigm. Other objectives must be considered, such as minimizing the energy consumption for transferring the π -containers (linked to the platform surface and the number of π -conveyors) or minimizing the π -vehicles total waiting time.

Compared to traditional cross-docks, in a π -cross-dock the congestion level can be higher. Indeed, because π -containers move on their own, there is no need for space around to maneuver handling trucks. Therefore, congestion-related indicators are less important. Similarly, the use of storage space or the average inventory level are not to be considered as performance measures for π -cross-docks since temporary storage should be eliminated. [Table 1](#) summarizes the comparison between the objective functions classically used in the cross-docking literature, and those needed for π -cross-docks.

Table 1: Main differences between traditional cross-docks and π -cross-docks

	Classical cross-dock	π -cross-dock
Objective functions	<ul style="list-style-type: none"> • makespan • distance traveled, labor cost • truck processing time • deviation • inventory level • congestion 	<ul style="list-style-type: none"> • π-container leadtimes • π-transits energy consumption • π-vehicles total waiting time • throughput
Internal transportation resources	<ul style="list-style-type: none"> • Forklifts + human workers • Conveyors 	<ul style="list-style-type: none"> • π-conveyors • π-sorters

Note that cross-docks, like all infrastructures and transport systems, must take global sustainability and its three economic, environmental and societal pillars into account. As a consequence, all decisions must be taken according to this balanced view, and sustainability-related

performance measures should be included in both classical and π -cross-dock optimisation problems. Social and environmental indicators are therefore not included in Table 1, since they are a common point between both modes.

3. Strategic and tactical π -cross-dock optimization problems

Although Buijs et al. (2014) make a clear distinction between strategic and tactical problems in their classification, it is also clear that these two decision levels are closely related and most decisions are actually intertwined. Therefore, we chose to present together the strategic and tactical decisions as summarized in Figure 3. It is worth noting that this section will put emphasis on the relevance of the optimization problems to PI as a new paradigm, even though they could also be investigated for traditional cross-docking centers.

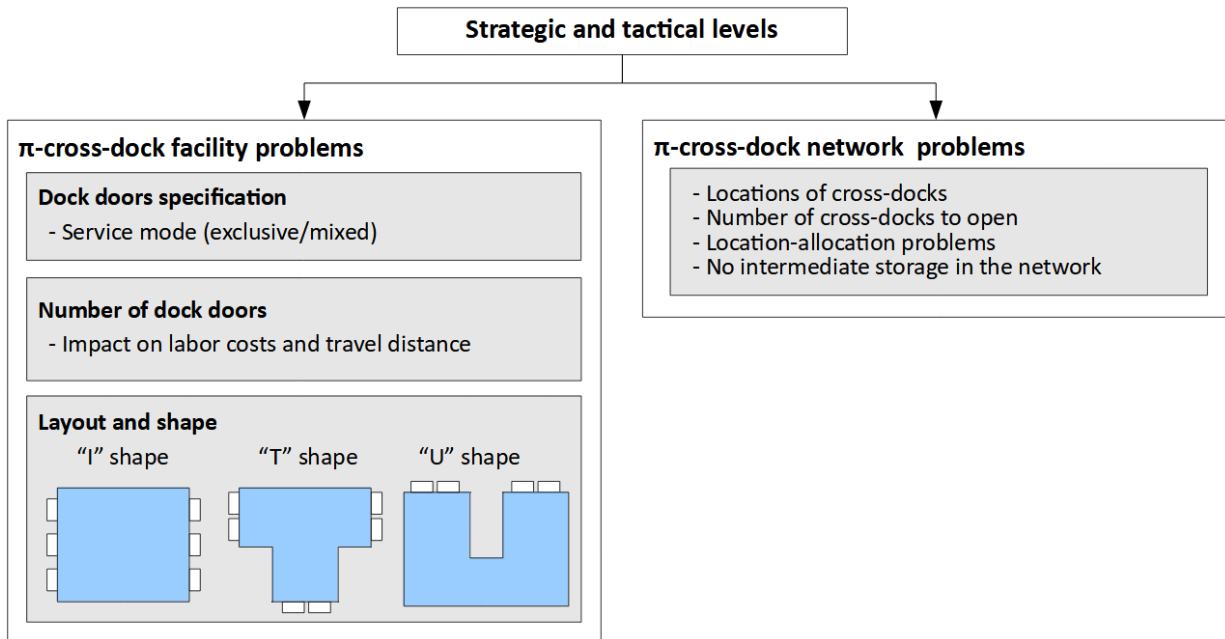


Figure 3: An overview on the strategic and tactical decisions in the π -cross-dock problems

3.1. Strategic and tactical π -cross-dock facility problems

Strategic and tactical cross-dock facility problems address decisions to be made on the long-term and/or mid-term regarding the facility processes.

3.1.1. Dock doors specification – definition of the service mode

The tactical decision of specifying the service mode of the doors of a cross-dock is a starting point for more strategic decisions regarding the cross-dock layout and its number of doors.

Boysen & Flidner (2010) define four different service modes: *exclusive* if each door is either exclusively dedicated to inbound or outbound operations; *mixed* if each door can process an intermixed sequence of inbound and outbound trucks; *exclusive/mixed* if a subset of doors is operated in exclusive mode and another in mixed door; and *given* (or *destination exclusive* in Ladier & Alpan (2015)) if the door assignment of each truck is given by each truck’s destination.

As noted by Ladier & Alpan (2015), “a destination-exclusive mode of service may lower the efficiency of the dock utilization, but is still widely used because [...] loading is faster when the workers know by experience where to reload each unit.” Because π -operations rely more on automation than on workers’ experience and habits, a mixed mode of service seem more appropriate in road-based π -cross-docks in order to increase the dock utilization rate.

In road-rail and water-road π -cross-docks, the truck doors use an exclusive mode of service (Montreuil et al., 2013b; Ballot et al., 2012b).

3.1.2. Number of dock doors

Determining the exact number of doors needed when designing the facility is a more complex problem in a mixed service mode than in a destination-exclusive mode, in which “the number of shipping doors is relatively easy to determine because [...] if each destination requires one door, then the number of shipping doors equals the number of destinations” (Bartholdi & Gue, 2004). Besides, since a π -cross-dock handles big volumes of π -containers from a limited set of origins and destinations, more than one door per destination may be needed, also in line with Bartholdi & Gue (2004) who claim that “a high-flow destination may require more than one door to provide sufficient ‘bandwidth’³ to the destination”.

A new problem is therefore specified: determining the number of doors needed in a π -cross-dock with a mixed mode of service and a limited set of high-flow origins and destinations. Montreuil et al. (2012) mention it when designing a road-road π -cross-dock; they use simple average time-based ratios (if a truck is loaded or unloaded in 10 minutes at a gate, then one gate is needed per four or five arrivals per hour) but underline the need for analytic models, notably exploiting queuing network theory.

For rail and water-based π -cross-docks, the problem is less decisive because it seems impractical and much too space-consuming to unload or load too many trains or barges at once: according to Boysen et al. (2012), a typical rail-road terminal consists of between two and four parallel tracks and a maximum of six is possible.

3.1.3. Shape and layout of the cross-dock

Studies by Bartholdi & Gue (2004) and Carlo & Bozer (2011) aim at finding the shape (I, L, T, U, H, E, X, etc.) for a road-road cross-dock that minimizes the labor costs, assumed to be proportional to the average (euclidean) travel distance of material handling equipment. Kapetanios et al. (2009) compare the performance of cross-docks depending on the number of receiving and shipping docks. Implicit assumptions are made regarding cross-docking operations: trucks are loaded/unloaded from the rear, and the unloaded material must sit on the dock in front of the door after unloading and before loading. These different assumptions do not hold any more in the case of a π -cross-dock.

If routing inside the π -cross-dock is operated by a 2-dimensional grid of π -conveyors, then the distances to consider are rectilinear rather than euclidean, which leads to more easily tractable models (the rectilinear distance is linear whereas the euclidean distance is not). Besides, a π -truck can be unloaded from any side, therefore the narrow docks used by Bartholdi & Gue (2004) could be questioned in the PI context. Finally, the objective functions should aim at minimizing energy consumption for transferring the π -containers, minimizing the π -vehicles total waiting time or maximizing throughput (see subsection 2.1.2).

3.2. Strategic and tactical π -cross-docking network problems

In the cross-docking literature, determining the locations and number of cross-docks within a network is usually done together with the allocation of freight flows, which corresponds to a “location-allocation problem” from the broader point of view of the facility location community (Alumur & Kara, 2008). Recent studies such as Klibi et al. (2016) have shown the impact

³Note the Internet metaphor, used here by Bartholdi & Gue a long time before the emergence of the Physical Internet concept.

of transportation on location-allocation decisions. Their results show how the uncertainty of demands impacts the assignment of the customers. Note that the purely strategic problem is a pure transportation network problem: cross-docking only becomes a special case if the tactical level is simultaneously taken into account, particularly the absence of intermediate storage. As the impact of transportation on CO₂ emissions can be huge, the sustainability aspect has been increasingly considered in the optimization of such problems (Coyle et al., 2015; Dubey et al., 2017; Tirkolaee et al., 2020).

According to Buijs et al. (2014), most articles addressing cross-docking network design problems consider a network composed of a set of origins, a set of destinations, and a single layer of cross-docks in between. In the PI paradigm, this typical 2-segment cross-docking network configuration is shifted towards a multi-segment network: there can be much more than one π -cross-dock between origin and destination. Montreuil (2011) uses as an example a Los Angeles - Québec trip split into 17 segments; each segment covers a trip of less than 6 hours, so that all drivers can get home after a working day, and the π -container therefore transits through 16 π -hubs on the way. Designing such a network is a special case of a hub-covering problem (Farahani et al., 2013) that is yet to specify, taking multi-modal point of view into account (Alumur et al., 2012) as done in the π -context by Sun et al. (2018). In a tactical planning study, Taherkhani et al. (2022) propose a tactical planning system that takes into consideration both the supply and demand at the same time. A mathematical formulation is presented to generate a transportation plan while maximizing the total profit of the system. The suggested model was validated on real size problem sets.

4. Operational π -cross-dock optimization problems

Montreuil et al. (2012) describe the different operational decisions to be taken in a π -cross-dock as follows : “(1) which truck the driver is to drive next, leaving when and to where; (2) when applicable, which trailer the truck is to pull next; (3) the set of π -containers to be loaded on the trailer or truck as appropriate; and (4) the next destination for each π -container to be transhipped as well as the specific trailer or truck on which it is to be loaded.” This section further details the related decision problems, both at the scale of the facility and regarding the entire network. An overview of these problems is illustrated in Figure 4.

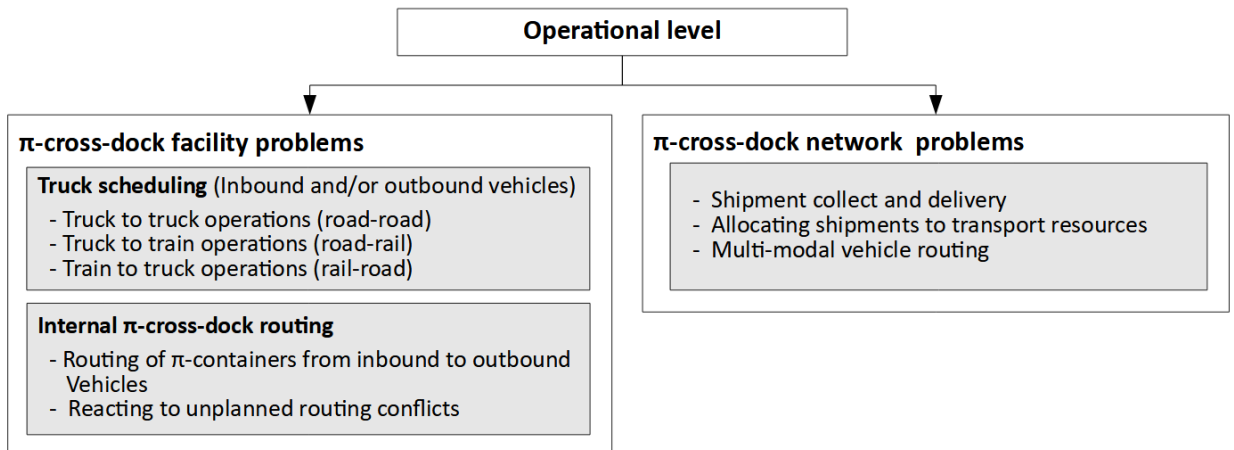


Figure 4: An overview on the operational decisions in the π -cross-dock problems

4.1. Operational π -cross-dock facility problems

Operational problems at the scale of the cross-dock facility aim at specifying the allocation of resources over time. Two major problems can be considered, truck scheduling and internal

routing. Since truck scheduling is out of the scope of this work, we only refer to (Ladier & Alpan, 2015; Theophilus et al., 2019; Gaudioso et al., 2021). And it will not be further discussed. Now our discussion will focus on the second problem.

4.1.1. Internal π -cross-dock routing

Internal π -cross-dock routing problem is not formally identified by Buijs et al. (2014), probably because routing is done intuitively by human workers in traditional cross-dock. However, in a π -cross-dock, the very high level of automation requires to solve internal routing problems.

To route container groups through the facility, Pach et al. (2014a) proposes a potential field approach, while Sallez et al. (2015a); Vo et al. (2018) propose a hybrid control architecture articulating a global control layer (calculating an optimal route with a classical OR approach) and a local control layer. At local level, a π -container reacts to unplanned routing conflicts by negotiating with its neighbors. The multi-agent based approach is favored for its capability to react to uncertainty (variability in the arrival mix, truck/train punctuality, conveying system breakdowns). Assembling consolidated trailer loads into a structurally sound composition is a new problem arising in the specific context of the π -cross-dock. In a similar context, Pach et al. (2014b) propose a multi-agent based simulation to validate a composition strategy in which each π -container groups itself with others before loading in order to accelerate the overall transshipment.

This also concerns the aggregation/de-aggregation decision process of π -containers in addition to their routing. Indeed, according to the technology used to route π -containers, it may be useful to aggregate or de-aggregate some of them before or during the routing. This operational decision holds also true when facing unexpected events for example. More, if destination nodes are different, and if several π -containers contain batches of similar products, aggregation and de-aggregation decisions may be taken to optimize lead times for example. This problem is also linked to the composition problem and the truck filling algorithms.

4.2. Operational π -cross-docking network problems

This subclass problem, also termed as network scheduling problem in Buijs et al. (2014), mainly concerns two issues: shipment dispatching, i.e., how to dispatch and how many shipments onto a given transport service, and vehicle routing to collect and deliver shipments for cross-dock. Both are little studied in the literature. Sarraj et al. (2014a) seem the first work that has addressed the network scheduling problem. They simulated the policy of collecting shipments from source to the closest π -hub for single or multi-modal transport. However, the work does not consider time windows at hubs or synchronization in transport, as they only set a maximal waiting time of 3 hours at each π -cross-docking. Some other works (Kong et al., 2016) suggest auction mechanisms to allocate shipments to transport services, or dynamic pricing to manage the collection and delivery routing related to π -hub (Qiao et al., 2020). In a case study of automotive industry, Serrano et al. (2021) formulated a mixed-integer programming model for cross-docking facilities. The objective in the model is to minimize the transportation, internal resources and storage costs. The results showed a 13% decrease in total cost. Vanajakumari et al. (2022) considered a network of hybrid cross-docks by using Free Zones in an integrated supply chain. A mathematical formulation is presented in addition to heuristics to minimize the inventory and logistics costs. Cota et al. (2022) integrated the open vehicle routing problem with cross-dock truck scheduling to minimize the penalties caused by the delays. The problem is formulated as a mixed-integer linear programming model. Due to the complexity of the problem, a Variable Neighborhood Search-based meta-heuristics and robust dynamic algorithm were proposed for large instances. The results validates the performance of

the proposed algorithms in terms of solution quality and computational times. These study do not take into account synchronization nor sustainability, both of which should be considered in future research.

5. Key findings from the literature review

The review of cross-docking problems from the strategic and tactical levels shows that most researches were focused on classical design problems such as the number of docks and the shape and layout of the cross dock facility. Regarding π -cross-docks, only a few theoretical designs were proposed, mainly for road-rail and rail-road π -hubs, with predefined dimensions (number of docks, wagons, etc). Even though a roadmap ([ALICE-Roadmap, 2021](#)) has been defined for future directions on the PI, the studies on strategic and tactical levels are limited to case studies on small network instances. An important direction of future works on the π -cross-docking problems concerns the cost of such infrastructures to implement the PI paradigm in the real world. No studies are done yet on the cost of such infrastructures for logistics companies.

On the operational level, various works focus mainly on optimization problems related to truck scheduling and vehicle routing. Most of these studies are limited to the optimization aspects and ignore generally the impact of the facility design on the efficiency. Indeed, these studies are based on one specific design.

The analysis of the literature in the previous sections shows the lack of studies in three main fields. On the operational level, a lack of research can be seen in both π -cross-dock facility and network problems. For facility problems, in terms of π -containers routing, only a couple of simulation studies were done. On network problems, multi-modal networks that combine different transportation resources have not been addressed yet.

Figure 5 summarizes the impact of decisions in the strategic and tactical decision levels on the operational level and vice versa. The parameters of the hub facility and network design, such as number of docks and arrival time of vehicles, are considered as input values for the operational level, while the solutions on each hub (vehicles departure times for examples) can impact the strategic decisions of the cross docks in long term horizon by increasing the vehicles flow on some hubs in the network .

Another issue that can be observed is the lack of studies combining both the π -cross-docking facility and network problems. Such studies are needed to evaluate the global logistics process in the PI from the three levels – strategic, tactical, and operational. This will provide a global view on the impact of the PI on the sustainability and performance of the global supply chain. In addition, there is also a lack of studies that consider uncertainty and perturbations especially in π -cross-docking network problems. These disruptions can be managed in three different ways, as described by [Paul et al. \(2016\)](#): Mitigation approaches in before the occurrence of the disruption, recovery approaches after the disruptions, and passive acceptance approaches that do not require any action after the occurrence of the perturbations.

All models mentioned above are challenging to solve, since a large majority of them have been shown to be NP-hard. Different solution approaches can be found in the literature, from exact approaches to meta-heuristics, dedicated heuristics or hybrid approaches (mixing exact approaches and heuristics, or simulation and optimization). The interested reader can refer to the previously mentioned literature review papers ([Ladier & Alpan \(2015\)](#); [Buijs et al. \(2014\)](#); [Theophilus et al. \(2019\)](#)) for more detailed analyses on the solving approaches. Let us note however that no study so far focus on the differences between traditional cross-dock and π -cross-dock problems, in terms of solution approach. The higher level of automation of the Physical Internet logically requires a higher number of decisions to be taken, at a more detailed

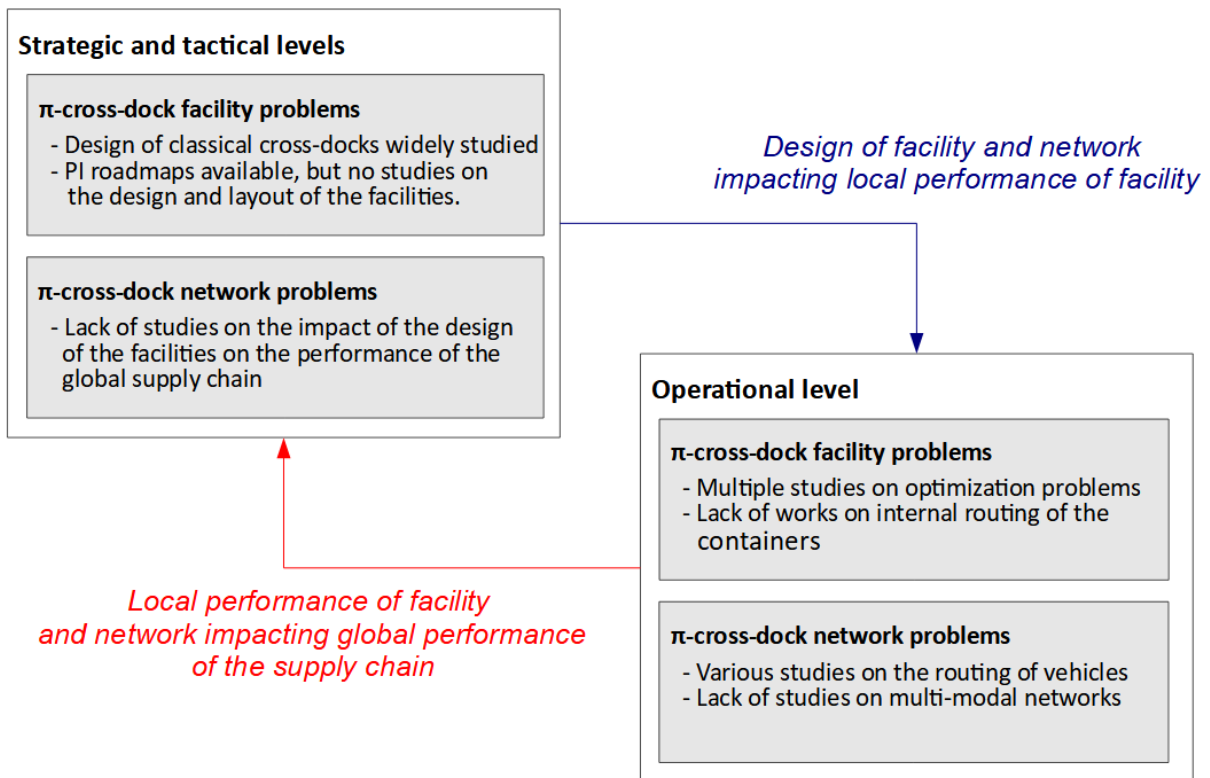


Figure 5: An overview on the analyzed literature of the PI from different decision levels

timescale ; but some characteristics of the problem (among which the rectilinear grid or the decentralization of some decisions, for example) can also reduce the complexity of the problem studied. Uncertainty might also be managed differently in both types of cross-docks, therefore requiring different solution approaches. This avenue of research is therefore of interest, and further investigations on the topic would be of interest for the community.

In order to start filling some of the gaps identified above, the next section will introduce an example of a multi-modal π -cross-docking model, with a numerical experiment to validate it. Multi-modal π -cross-docks are less studied compared to global supply chain problems such as pickup and delivery, routing and transportation problems, etc. To fill this gap in the literature, a rail-road π -cross-dock is chosen as an example to be formulated in the next section.

6. Modeling the rail-road π -cross-dock

This section illustrates one example of the π -cross-docking problems. A multi-modal rail-road cross-docking platform is presented as a case study to evaluate the conditions of sustainability of the π -cross-dock compared to the classical cross-dock. Therefore, both the classical and the PI rail-road cross-docks are modelled. The main objective of this model is to answer the following question: At what threshold of energy consumption can the π -hub be considered sustainable ?

It is important to mention that the main objective of mathematically formulating the PI and classical cross-dock in this section is to provide a perspective example on the sustainability of the π -hub. The goal of this section is not to provide detailed comparative numerical experiments on both cross-docks. Instead, it provides a mathematical formulation of the problem that can be used as a reference in future works on π -hubs to obtain optimal values on which different approaches can be compared to.

6.1. Assumptions

The following assumptions are considered, and illustrated in Figure 6:

- For both PI and classical rail-road cross-docks, a multi-modal transportation platform consisting of trains and trucks is considered: containers arriving by train to the cross-dock are then dispatched to the outbound trucks according to their next destinations. The loading time of one container into an outbound truck, and the changeover time of outbound trucks, are supposed to be fixed and known.
- The lengths of containers and the capacities of the outgoing trucks are the same in both PI and classical cross-dock.
- The unloaded π -containers are shipped towards different destinations. However, the routing of the outgoing trucks is not considered in the model.
- In the π -cross-dock, π -containers unloaded from the train are transferred to the trucks using a 2D grid composed of a large number of fully automated moving units named π -conveyor. Each π -conveyor is able to convey π -containers in four directions, can be controlled in real-time, and is maintained in a reactive or predictive way.
- In the classical cross-dock, π -containers unloaded from the train are transferred to the trucks using forklifts. The forklifts are assumed to be available in sufficient number.

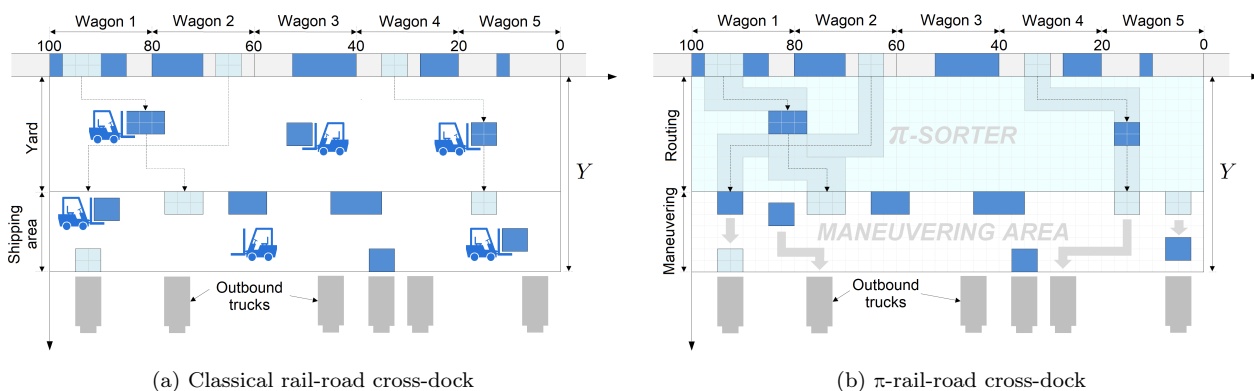


Figure 6: Organisation of the PI and classical rail-road cross-docks considered

6.2. Mathematical formulation

Both cross-dock operations management problems are formulated mathematically as Multi-Objective Mixed Integer Programs (MO-MIP1 for the classical cross-dock and MO-MIP2 for the π -cross-dock). The formulation and notations are inspired from [Chargui et al. \(2019\)](#) who consider two conflicting objectives: F_1 , the number of outgoing trucks used, and F_2 , the distance covered by all π -containers. Authors in [Chargui et al. \(2019\)](#) minimize these objectives in a lexicographic order. Here however, the objective function is an aggregate weighted function that includes both objectives F_1 and F_2 ; this will enable to identify the Pareto optimal front. Moreover, in this study, we normalize both objective functions which have different units. Unlike lexicographic optimization, the aggregate weighted sum provides a various number of scenarios by varying the weighting factor α , which provides more accuracy in the priorities of the normalized objective functions. In addition, the previous studies ([Chargui et al., 2020, 2019](#)) that addressed the π -hubs (road-rail and rail-roads) from the PI perspective only without

considering any comparison to the classical version of the π -hubs. For example, in [Chargui et al. \(2019\)](#), in addition to using lexicographic optimizations, the authors formulated and solved the mathematical model only for the rail-road π -hub. However, the model in this paper handles both classical and π -hub cross-dock which allows the possibility of comparing both hubs in terms efficiency by minimizing the number of trucks and sustainability using the energy consumption threshold.

Definition sets.

- \mathcal{N} set of containers (either classical containers or π -containers depending on the cross-dock considered);
- \mathcal{D} set of possible destinations for the containers;
- \mathcal{K} set of outbound docks;
- \mathcal{H} set of outbound π -trucks or trucks, depending on the cross-dock considered.

Problem data.

- C_i^{CD} energy consumption for moving container $i \in \mathcal{N}$ by 1 meter, in the classical cross-dock;
- C_i^{PI} energy consumption by one π -conveyor to move π -container $i \in \mathcal{N}$ by the length of the π -conveyor;
- I time needed to load one container into an outbound truck;
- V changeover time : time needed to switch from one outbound truck to another at a given dock.
- Y width of the cross-dock, i.e. distance from the train to the loading docks
- D_{ik}^{CD} Euclidean distance from the initial position of container i to dock k (in meters)
- D_{ik}^{PI} Manhattan distance from the initial position of π -container i to the dock k (in meters)
- L_i length of container $i \in \mathcal{N}$;
- $G_{di} = 1$ if container $i \in \mathcal{N}$ is headed to destination $d \in \mathcal{D}$, 0 otherwise;
- Q capacity of the outbound trucks;
- M a big positive number.

Decision Variables.

- z_{ih}^{CD} distance (in meters) traveled by the forklift which transfers container $i \in \mathcal{N}$ to outbound truck $h \in \mathcal{H}$, in the classical cross-dock;
- z_{ih}^{PI} number of π -conveyor units used by π -container $i \in \mathcal{N}$ to get to the outbound truck $h \in \mathcal{H}$, in the π -cross-dock;
- $x_{hk} = 1$ if outbound truck $h \in \mathcal{H}$ is assigned to dock $k \in \mathcal{K}$, 0 otherwise;
- $p_{ih} = 1$ if container $i \in \mathcal{N}$ is assigned to outbound truck $h \in \mathcal{H}$, 0 otherwise;
- $a_{hd} = 1$ if destination $d \in \mathcal{D}$ is assigned to outbound truck $h \in \mathcal{H}$, 0 otherwise;
- $v_h = 1$ if outbound truck $h \in \mathcal{H}$ is loaded, 0 otherwise;
- $n_{hg} = 1$ if outbound trucks $h \in \mathcal{H}$ and $g \in \mathcal{H}$ ($h \neq g$) are assigned to the same dock and h is a predecessor of g , 0 otherwise;
- b_h starting time for the loading operation at outbound truck $h \in \mathcal{H}$;
- q_h completion time of the loading operation at outbound truck $h \in \mathcal{H}$.

Objective function. Two conflicting objectives are considered, for both a classical and a π -cross-dock. The first objective (F_1) is the number of outgoing trucks used, for both cross-docks. The second objective (F_2) captures the distance covered by all π -containers, in two different manners depending on the cross-dock considered:

- In the classical cross-dock, it is the total cost of transferring all containers ;
- In the π -cross-dock, it is the total number of π -conveyors used to transfer the π -containers.

The objectives to be minimized for both types of cross-dock are as follows:

$$F_1 = \sum_{h \in \mathcal{H}} v_h \quad F_2^{\text{CD}} = \sum_{i \in \mathcal{N}} C_i^{\text{CD}} \sum_{h \in \mathcal{H}} z_{ih}^{\text{CD}} \quad F_2^{\text{PI}} = \sum_{i \in \mathcal{N}} C_i^{\text{PI}} \sum_{h \in \mathcal{H}} z_{ih}^{\text{PI}}$$

Let us denote by α the weighting coefficient ($0 \leq \alpha \leq 1$). Before normalization, the objective function is formulated as follows for both PI and classical cross-docks:

$$\min z_\alpha = \alpha F_1 + (1 - \alpha) F_2$$

The objective function as a normalized weighted sum. Multi-objective problems can be tackled using various approaches such as the weighted aggregation, lexicographic goal programming or Pareto-based approaches. Since F_1 and F_2 have different units, in this case a normalized weighted sum is used to generate the Pareto front, by converting the different units into dimensionless values normalized between 0 and 1 (Grodzevich & Romanko, 2006). *Ideal* and *Nadir* points as described in Demir et al. (2014) are used for the normalization, since they provide the best normalization results according to Grodzevich & Romanko (2006).

The ideal point (I_{F_1}, I_{F_2}) represents a virtual point (not reachable in practice) when both objectives F_1 and F_2 reach their best possible values simultaneously:

$$I_{F_1} = z_{\alpha=1} \quad I_{F_2} = z_{\alpha=0}$$

The Nadir point (N_{F_1}, N_{F_2}) on the other hand, gives a baseline that is reachable in practice. N_{F_1} is the optimal value of F_1 when F_2 is constrained to take its best value I_{F_2} :

$$N_{F_1} = z_{\alpha=1} \text{ s.t. } F_2 = I_{F_2}$$

And symmetrically for N_{F_2} :

$$N_{F_2} = z_{\alpha=0} \text{ s.t. } F_1 = I_{F_1}$$

Let us call $\overline{F_1}$, $\overline{F_2^{\text{CD}}}$ and $\overline{F_2^{\text{PI}}}$ the normalized versions of F_1 , F_2^{CD} and F_2^{PI} , respectively. Their values are obtained as follows:

$$\overline{F_1} = \frac{F_1 - I_{F_1}}{N_{F_1} - I_{F_1}} \quad \overline{F_2^{\text{CD}}} = \frac{F_2^{\text{CD}} - I_{F_2}}{N_{F_2} - I_{F_2}} \quad \overline{F_2^{\text{PI}}} = \frac{F_2^{\text{PI}} - I_{F_2}}{N_{F_2} - I_{F_2}}$$

Model. The model is written as follows:

$$\begin{aligned}
\min \quad & z_\alpha = \alpha \overline{F_1} + (1 - \alpha) \overline{F_2} \\
\text{s.t.} \quad & \sum_{h \in \mathcal{H}} p_{ih} = 1 && \forall i \in \mathcal{N} && (1) \\
& \sum_{i \in \mathcal{N}} p_{ih} L_i \leq Q && \forall h \in \mathcal{H} && (2) \\
& p_{ih} + p_{jh} \leq \sum_{d \in \mathcal{D}} G_{di} G_{dj} + 1 && \forall i \in \mathcal{N}, j \in \mathcal{N} : i \neq j, h \in \mathcal{H} && (3) \\
& p_{ih} \leq v_h && \forall i \in \mathcal{N}, h \in \mathcal{H} && (4) \\
& a_{hd} \leq G_{di} + 1 - p_{ih} && \forall i \in \mathcal{N}, h \in \mathcal{H}, d \in \mathcal{D} && (5) \\
& z_{ih}^{CD} \geq D_{ik}^{CD} - M(2 - (p_{ih} + x_{hk})) && \forall i \in \mathcal{N}, k \in \mathcal{K}, h \in \mathcal{H} && (6.1) \\
& z_{ih}^{PI} \geq D_{ik}^{PI} - M(2 - (p_{ih} + x_{hk})) && \forall i \in \mathcal{N}, k \in \mathcal{K}, h \in \mathcal{H} && (6.2) \\
& v_h = \sum_{d \in \mathcal{D}} a_{hd} && \forall h \in \mathcal{H} && (7) \\
& \sum_{k \in \mathcal{K}} x_{hk} = v_h && \forall h \in \mathcal{H} && (8) \\
& x_{hk} + x_{gk} - 1 \leq n_{hg} + n_{gh} && \forall k \in \mathcal{K}, h \in \mathcal{H}, g \in \mathcal{H}, h \neq g && (9) \\
& n_{hg} + n_{gh} \leq 1 && \forall h \in \mathcal{H}, g \in \mathcal{H} && (10) \\
& b_g \geq q_h + V - M(1 - n_{hg}) && \forall h \in \mathcal{H}, g \in \mathcal{H} && (11) \\
& q_h = b_h + I \sum_{i \in \mathcal{N}} p_{ih} && \forall h \in \mathcal{H} && (12) \\
& x_{hk}, p_{ih}, a_{hd}, v_h, n_{hg} \in \{0, 1\} && \forall i \in \mathcal{N}, k \in \mathcal{K}, d \in \mathcal{D}, h \in \mathcal{H}, g \in \mathcal{H} && (13) \\
& z_{ih} \geq 0, b_h \geq 0, q_h \geq 0 && \forall i \in \mathcal{N}, \forall h \in \mathcal{H} && (14)
\end{aligned}$$

The proposed mathematical models (MO-MIP1 and MO-MIP2) have the same constraints except for constraints that calculate the variables z_{ih}^{CD} for the classical hub in constraint 6.1, and z_{ih}^{PI} for the π -hub in constraint 6.2. In constraint 1, a π -container should be assigned to one truck without exceeding its capacity in constraint 2. Constraints 3 - 5 manage the destinations of the trucks depending on the π -containers assigned to them. Constraint 6.1 calculates z_{ih}^{CD} which is the distance of forklifts for each π -container i in the classical hub. In constraint 6.2, z_{ih}^{PI} is the number of π -conveyors units used to transfer the π -containers to the outbound trucks. In constraints 7 and 8, if a truck should be used it will be assigned to a dock. Constraints 9 and 10 manage the order of receiving trucks at the docks. Constraints 11 and 12 calculate the start and the end of the truck loading operations for each outbound truck $h \in \mathcal{H}$. Constraints 13 and 14 state the binary and non-negativity constraints on all variables.

6.3. Numerical experiments and model validation

The objective of this subsection is to validate the proposed mathematical formulation for the classical cross-dock model. Different values of the weighting coefficient α are tested (between 0 and 1 with a 10^{-1} step). The objective is to obtain the optimal Pareto front in the classical cross-dock. Then, the obtained Pareto front threshold can be used as a reference to assess the sustainability of the π -cross-dock.

All tests are performed with IBM CPLEX Solver (Version 12.9) on a personal computer with Intel^(R) Core^(TM) i3 2.40 GHz CPU and 4 GB of RAM. A time limit of 1 hour was set on CPLEX and the best solution found is returned after this time.

Both models are tested on a small problem set of a train carrying several π -containers with one or two destinations and 6 available outgoing trucks. The main parameters are presented in Table 2 while the values used for D_{ik} and G_{di} are in Appendix A. The energy consumption of the forklifts depends on the size of each π -container and especially its weight. We assume that the π -containers have the same weight. We suppose the forklifts run on an average indoor speed of 6 km/h (Pashkevich et al., 2019). To illustrate the forklifts electricity consumption, the forklifts used in this study consumes an average of 17 kWh per hour (KalmarGlobal, 2021).

Results and discussion

The obtained results are illustrated in Figure 8 and detailed in Table 3. In Figure 8, the four lines present the optimal Pareto front of both objectives F_1 and F_2^{CD} in the classical

Table 2: Parameters values in the problem sets

Parameters	Values
Number of π -containers ($ \mathcal{N} $)	$\{8, 10\}$
Number of available trucks ($ \mathcal{H} $)	6
Number of destinations ($ \mathcal{D} $)	$\{1, 2\}$
Containers lengths (L_i)	[1.2m, 6m]
Truck capacity (Q)	15.6 m
Changeover time (V)	5 min
Loading time (I)	1 min
Width of the cross-dock (Y)	12 m
Average energy consumption (C_i^{CD})	2.834×10^{-3} kwh/m
Containers destinations (G_{di})	Binary $\{0, 1\}$

Table 3: Detailed results on the problem sets ($\alpha \in [0, 1]$)

α	$D = 1, N = 8$			$D = 1, N = 10$			$D = 2, N = 8$			$D = 2, N = 10$		
	F_1	F_2^{CD} (m)	F_2^{CD} (kWh)	F_1	F_2^{CD} (m)	F_2^{CD} (kWh)	F_1	F_2^{CD} (m)	F_2^{CD} (kWh)	F_1	F_2^{CD} (m)	F_2^{CD} (kWh)
0.0	6	98,433	0,279	6	126,296	0,358	6	104,223	0,295	6	132,875	0,376
0.1	6	98,433	0,279	6	126,296	0,358	6	104,223	0,295	6	132,875	0,376
0.2	6	98,433	0,279	4	132,212	0,375	6	104,223	0,295	6	132,875	0,376
0.3	5	100,689	0,285	4	132,212	0,375	6	104,223	0,295	5	137,680	0,390
0.4	4	103,648	0,294	3	139,660	0,396	5	109,249	0,310	5	137,680	0,390
0.5	3	108,547	0,308	3	139,660	0,396	5	109,249	0,310	4	152,363	0,432
0.6	3	108,547	0,308	3	139,660	0,396	3	136,122	0,386	4	152,363	0,432
0.7	2	120,929	0,343	3	139,660	0,396	3	136,122	0,386	3	187,655	0,532
0.8	2	120,929	0,343	2	179,435	0,508	3	136,122	0,386	3	187,655	0,532
0.9	2	120,929	0,343	2	179,435	0,508	3	136,122	0,386	3	187,655	0,532
1.0	2	120,929	0,343	2	179,435	0,508	3	136,122	0,386	3	187,655	0,532

hub. In table 3, F_2^{CD} is presented in two units, as distance in meters (m) and as a electricity consumption (kWh).

In order to test the sensitivity of both objective functions different combination of destinations (D) and number of containers (N) are tested. Figure 8 shows the Pareto front of different scenarios. In order to consider the π -hub as a sustainable solution, the energy consumption of the used π -conveyors should be in the zone under the Pareto front in Figure 8. For example, for $D = 1$ and $N = 10$ when $\alpha = 0.5$ in Figure 8, the total energy consumption cost of the forklifts is 0.396 kWh. Therefore, the π -hub can be considered sustainable if the energy consumption cost of one π -conveyor unit is less than 0.396 kWh.

Figure 7 shows the sensitivity of the objective functions to variation of the number of π -containers. The weighting factor α is set to 0.5.

Extensive experiments on multiple problem sets with different configurations are needed to validate the positive impact of the PI on the global sustainability of cross-docking hubs. Evaluating different models and designs of π -conveyors is necessary to assess the sustainability of the π -hub.

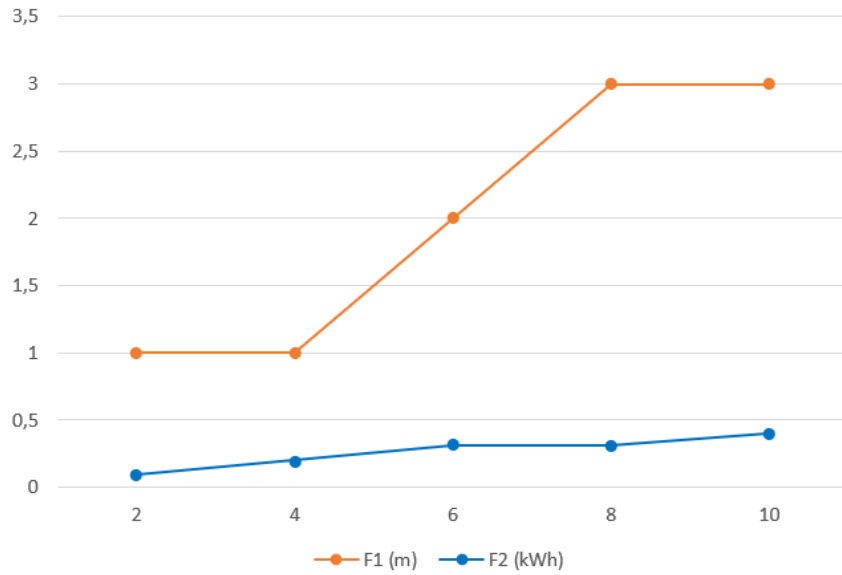


Figure 7: Impact of the number of containers on the two objectives

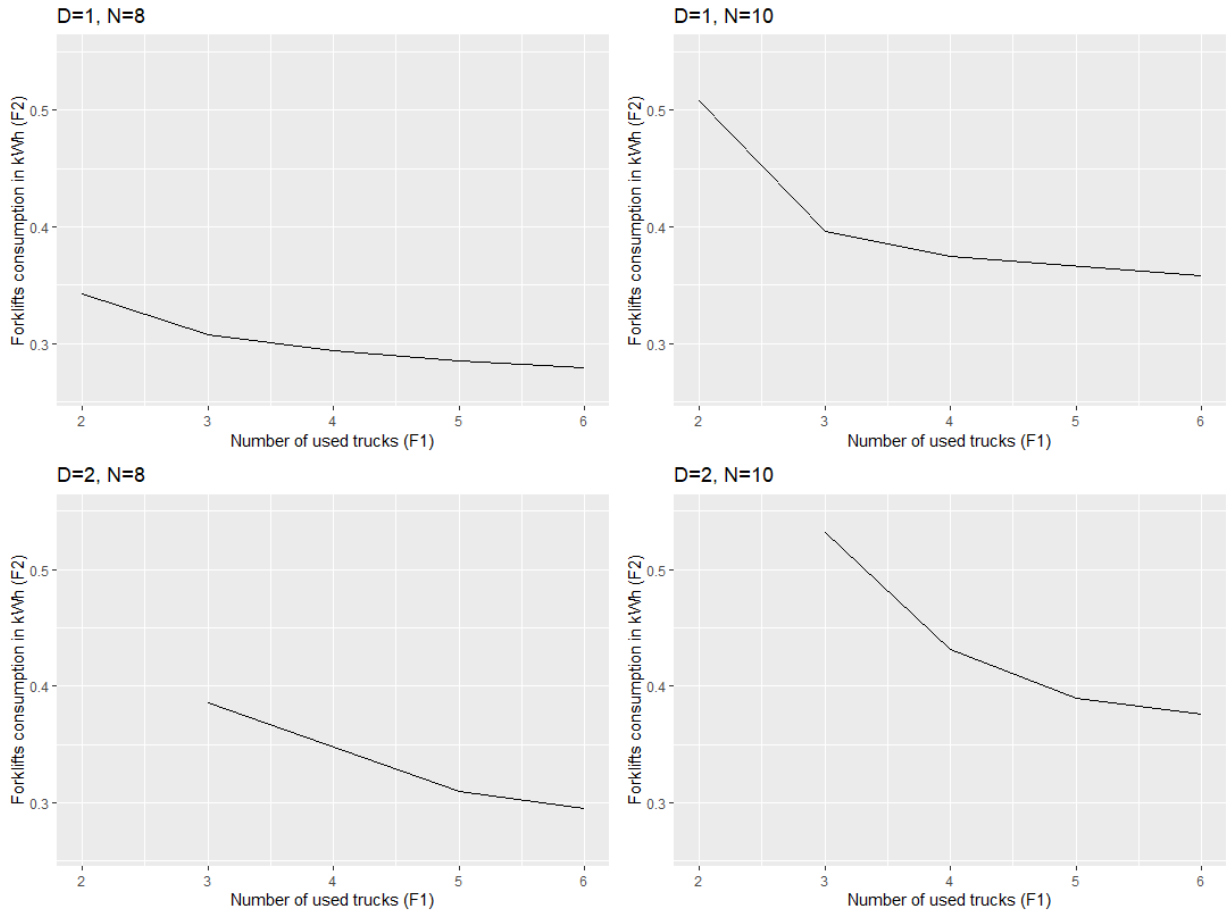


Figure 8: Trade-off between the number of used trucks F_1 and the forklifts energy consumption cost F_2^{CD}

7. Conclusion

This paper proposed an updated review of research works on the sustainable aspect of the cross-docking problems and the innovations brought by the new paradigm of Physical Internet. The three sustainable decision levels (strategic, tactical and operational) were considered in the review of both classical and π -hubs. After analyzing the literature and presenting new research

avenues, an example of a cross-docking platform was selected as a case study to evaluate the sustainability of the π -version of the hub. Two multi-objective mathematical models were proposed to evaluate the sustainability conditions of the π -hub.

This work also provides managerial insights that are practically useful for cross-docking services providers and managers. First, it is foreseeable that efficiency of cross-docking will become even more critical for multi-modal transportation, as witnessed during the COVID pandemic. The discussion of traditional and PI cross-docking centers has pointed out an effective way to improve efficiency via redesigning the centers and operations. The distinctive features of PI cross-docks should be considered in facility design or operations management. Second, the numerical study clearly showed the potential of PI-cross-docking centers and they could be more sustainable with proper technologies. This suggested that the selection of technologies should be carefully investigated at the facility design stage.

Up to now in our work, the human and social dimensions of sustainability in PI cross-dock were not considered. Even though the π -cross-docks are highly automated platforms, human interventions remain necessary especially in case of machine failures or malfunctioning. This should be addressed in the near future.

As a new paradigm towards the sustainability of the global supply chain, the concept of PI continues to generate various research problem especially for the operations research and recently for the artificial intelligence community as well. As a possible extension of this work, different configurations of inter-modal cross-docks can be considered (rail-rail hubs, water-rail hubs, etc). The performance of these inter-modal cross-docks could be evaluated using mathematical modelling with different multi-objective approaches such as ε -constraint or goal programming methods.

In real world context, when disruptions occur, the obtained solutions become useless. Another interesting perspective is to consider the possible disruptions in the cross-docking platforms, such as truck delays, transportation resources failures, etc. Different approaches can be used, proactive ones (chance constrained programming, coupling simulation with optimization, etc) or reactive ones (multi-agent simulation, etc). Moreover, artificial intelligence approaches such as machine learning and neural networks can also be combined with optimization methods to predict demand forecasting for example.

8. Acknowledgements

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Appendix A. Problem set parameters

$$\begin{array}{l} \text{Problem set } (D = 1, N = 8): \\ L_i : 3.6 \quad 4.8 \quad 1.2 \quad 2.4 \quad 3.6 \quad 2.4 \quad 3.6 \quad 6.0 \\ G_{di} : 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \end{array}$$

$$\begin{array}{l} \text{Problem set } (D = 1, N = 10): \\ L_i : 1.2 \quad 3.6 \quad 2.4 \quad 4.8 \quad 2.4 \quad 2.4 \quad 1.2 \quad 3.6 \quad 6.0 \quad 3.6 \\ G_{di} : 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \end{array}$$

$$\begin{array}{l} \text{Problem set } (D = 2, N = 8): \\ L_i : 3.6 \quad 4.8 \quad 1.2 \quad 2.4 \quad 3.6 \quad 2.4 \quad 3.6 \quad 6.0 \\ G_{di} : 1 \quad 0 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1 \\ \quad \quad 0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0 \quad 1 \quad 0 \end{array}$$

$$\begin{array}{l} \text{Problem set } (D = 2, N = 10): \\ L_i : 1.2 \quad 3.6 \quad 2.4 \quad 4.8 \quad 2.4 \quad 2.4 \quad 1.2 \quad 3.6 \quad 6.0 \quad 3.6 \\ G_{di} : 1 \quad 0 \quad 0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0 \quad 1 \quad 1 \\ \quad \quad 0 \quad 1 \quad 1 \quad 0 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 0 \end{array}$$

Distances:

$$D_{ik}^{CD} = \begin{array}{cccccccc} 13.416407865 & 12.649110641 & 18.439088915 & 26.832815730 & 36.055512755 & 45.607017004 & 55.317266744 & 65.115282384 \\ 16.278820596 & 12.041594579 & 15.000000000 & 22.472205054 & 31.384709653 & 40.804411526 & 50.447993023 & 60.207972894 \\ 24.186773245 & 16.278820596 & 12.041594579 & 15.000000000 & 22.472205054 & 31.384709653 & 40.804411526 & 50.447993023 \\ 32.310988843 & 23.323807579 & 15.620499352 & 12.000000000 & 15.620499352 & 23.323807579 & 32.310988843 & 41.761226036 \\ 39.849717690 & 30.463092423 & 21.633307653 & 14.422205102 & 12.165525061 & 16.970562748 & 25.059928172 & 34.176014981 \\ 46.572524089 & 37.000000000 & 27.730849248 & 19.209372712 & 13.000000000 & 13.000000000 & 19.209372712 & 27.730849248 \\ 53.366656257 & 43.680659336 & 34.176014981 & 25.059928172 & 16.970562748 & 12.165525061 & 14.422205102 & 21.633307653 \\ 64.132674979 & 54.341512677 & 44.643028571 & 35.114099732 & 25.942243542 & 17.691806013 & 12.369316877 & 13.892443989 \end{array}$$

$$D_{ik}^{PI} = \begin{array}{cccccc} 18 & 16 & 26 & 36 & 46 & 56 & 66 & 76 \\ 23 & 13 & 21 & 31 & 41 & 51 & 61 & 71 \\ 33 & 23 & 13 & 21 & 31 & 41 & 51 & 61 \\ 42 & 32 & 22 & 12 & 22 & 32 & 42 & 52 \\ 50 & 40 & 30 & 20 & 14 & 24 & 34 & 44 \\ 57 & 47 & 37 & 27 & 17 & 17 & 27 & 37 \\ 64 & 54 & 44 & 34 & 24 & 14 & 20 & 30 \\ 75 & 65 & 55 & 45 & 35 & 25 & 15 & 19 \end{array}$$