IPIC 2021 | 8th International Physical Internet Conference

Modularization of Delivery and Transportation

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Abstract: *Traditional static and optimization based transportation planning and operation system has limitations on supporting highly dynamic, hyperconnected, multi-player logistics system in Physical Internet. Modularizing delivery and transportation can enable flexible transportation operations to adapt to such highly dynamic environment with potentially reduced planning effort. The modularization schemes are categorized into regional, hierarchical, and functional modularization. Regional modularization replaces a long route with many shorter routes, or modules, interconnected via PI hubs. Hierarchical modularization implements a multi-tier transportation system where each tier becomes a module connected via PI hubs. Functional modularization is to ensure each route serves a single functionality, each of which requires different resources. All three modularizations can increase flexibility of planning and operation while increasing the consolidation level and efficiency. Experimental results applying hierarchical and functional modularization for last mile delivery shows up to 27% of operational cost savings.*

Keywords: *Modularized transportation; Regional modularization; Hierarchical modularization; Functional modularization; Transportation design; Physical Internet*

1 Introduction

Efficient and cheap, yet fast and punctual, delivery and transportation are one of the main goal of logistics. Not surprisingly, there has been plethora of research and practice to improve transportation efficiency which ultimately can reduce cost and transportation-induced impacts on environment and society. The main challenge is to ensure the service capability, which is often measured as responsiveness and punctuality, while reducing costs. The growth of e-commerce, home delivery and globalization imposes even more challenges as origin and destination pairs become more diversified, each shipment size becomes smaller, and delivery lead time becomes tighter. Typically, such transportation problems are tackled by solving them with more advanced optimization modeling, such as stochastic optimization or online/dynamic routing, or solution methodologies, such as branch-and-price, metaheuristics or even machine learning (Gutierrez et al., 2018; Nazari et al., 2018; Koc et al., 2016). In fact, the transportation and routing optimization problems are one of the famous examples of mixed integer programs, which is well known to be a NP-hard problem (Toth & Vigo, 2014; Laporte, 2009). That is, in practice, companies spend substantial time and capital for finding an optimal transportation plan, which tends to be modified at the time of operations. However, for the Physical Internet based hyperconnected delivery and transportation operations, which is highly dynamic and where multiple players' operations are synchronized together, the traditional approach may not be suitable and can even be inefficient.

The Physical Internet (PI) is recently rising logistic paradigm shift (Montreuil, 2011). Here, we focus on the delivery and transportation in PI system (Kaboudvand et al., 2021; Kim et al., 2021). The traditional transportation and delivery planning methodologies are not easy to be applied in highly dynamic PI environment where multiple players are interacting. This paper aims to propose a flexible transportation planning scheme to facilitate PI transportation through modularization of delivery and transportation, as an extension of Kim et al. (2021) further developing transportation and delivery scheme. This is in line with the fundamental idea of the PI, a digital internet analogy applied for physical assets. The analogy clearly implies that modularization serves a key role under PI. Van Luik et al. (2020) provides good analogy and link between digital internet and PI. In this paper, we divide the transportation modularization into three types: regional, hierarchical, and functional modularization.

This paper contributes to literature by conceptualizing the modularized delivery and transportation and categorizing the modularization scheme into regional, hierarchical, and functional modularization. Then, the potential impact of modularized delivery is demonstrated via simulation-based experimental results in urban delivery. Through the conceptualization and simulation, we aim to develop a novel framework for delivery and transportation system to better facilitate PI operation. The structure of the paper is as follows. In Section 2, the modularized delivery and transportation is defined and conceptualized. Three types of modularization are described and linked to literature. Section 3 and 4 present the design and results of simulation-based experiments. Section 6 summarizes the paper and concludes with future research avenues.

2 Modularization of transportation and delivery

This section define modularization of delivery and transportation. We first review modularity in logistics and the hyperconnected delivery and transportation in PI context, from which the transportation modularization is motivated. Then, different types of modularization are defined, namely, regional, hierarchical, and functional modularization.

2.1 Modularity

Modularity is a general concept that has been used in various contexts such as science, software and programming and system design. Baldwin et al. (2000) defines a module as "*a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units*" and the core of modularization is to divide a complex system into smaller subsystems, which encapsulate their complexity in them and interact in the original system through interfaces, emphasizing the key concepts are *abstraction, information hiding,* and *interface*. Holtta and Salonen (2003) defines a module as "*a structurally independent building block of a larger system with well-defined interfaces*". In the context of supply chain, Bask et al. (2010) has provided the definition "*a modular system is a system built of components, where the structure ["architecture"] of the system, functions of components ["elements", "modules"], and relations ["interfaces"] of the components can be described so that the system is replicable, the components are replaceable, and the system is manageable*" through extensive literature review. Pekkarinen and Ulkuniemi (2008) identify the modularity into three categories: modularity in service, process and organization and emphasize the needs of good platform that links modules. All modularization definitions emphasize the independent components, interfaces, and system architecture where modules are connected to other modules. Another key feature we emphasis is, as stressed by Baldwin et al. (2000), each module should contain strongly-related elements that can be independently treated to other modules while inter-module dependency is minimized. Building upon the definition of module and modularization, we aim to apply the core logic of modularization to transportation and delivery system. Also, the paper aim to address how modularization of delivery and transportation can improve flexibility, reduce planning and operational complexity, and save costs, which are pointed out as a common benefits of modularization by Rajahonka (2013). Bask et al. (2010) categorized modularity in supply chain into modularity of product, production/process, supply chain/organization, and services. The transportation and delivery modularization discussed in the paper belongs to supply chain and service modularization.

2.2 Modularization for hyperconnected delivery and transportation

We define hyperconnected delivery and transportation as a *multi-player routing/shipping modularized by region, layer, and/or functionality enabling dynamic and broad range of flow consolidation*. The key notion in this definition of hyperconnected delivery and transportation is modularization. In this paper, a module is defined as a smallest planning and/or operation unit for transportation. For example, often the transportation to the last hub and the last mile delivery to customers are planned and operated separately, in which case, they can be considered as two separate transportation modules. Each module may be planned independently, served by different vehicles, or operated by different players. The major benefits of modular transportation stems from this characteristic. Meanwhile, in hyperconnected logistics, the modules are seamlessly interconnected with each other via standardized physical and digital interface. This is closely related to PI enablers of modular transportation, such as PI hubs (Ballot et al., 2012A; Meller et al., 2012) and containerization (Kaboudvand et al., 2021; Sternberg & Denizel, 2020; Gontara et al., 2018; Sarraj et al., 2014; Montreuil et al., 2010).

2.3 Regional modularization

Regional modularization is the most straightforward modularization scheme. It is to divide a long delivery route into multiple smaller and synchronized delivery routes by region. It lets each route covers smaller area. Montreuil (2011) describes it with an example of truck-based transportation from Quebec, Canada to LA, USA, where it is converted from long-haul to distributed multi-segment travel. Montreuil (2011) also emphasizes the flexibility of decision making achieved via such modularization, which can allow the use of other transportation modes such as rail for some segments. Ballot et al. (2012A) designed and applied open hub network to food distribution in France and showed remarkable results achieving regional modularization. The proposed network reduces the maximum length of trips by more than 71%, to 400 km. Sarraj et al. (2014) and Gontara et al. (2018) also modeled and experiment container routing problem with a network of PI hubs. Fazili et al (2017) further develop container routing model building on Sarraj et al. (2014). Figure 1 describes regional modularization where long routes can be modularized into shorter segments (or modules). Each module can be served in a regular work hour, and more consolidation can be achieved.

The regional modularization can facilitate flexible routing and dynamic consolidation by having more decision making and consolidation points. Also, with well-established network of PI hubs, each route module can be short enough to be served in regular working hour. This has positive impact of driver’s work environment, being able to ‘sleep-at-home’. It is one of the crucial factor to determine drivers’ quality of life (Ferrell, 2016). Improving work environment for drivers can also contribute to lower the operation cost by reducing driver turnover (Min & Lambert, 2002). Also, typically long haul routes are served by a driver team, not a single driver, which increase labor cost per mile. When the shorter route modules replace long hauls, it can reduce labor hour per travel mile as short route modules can be served by a single driver.

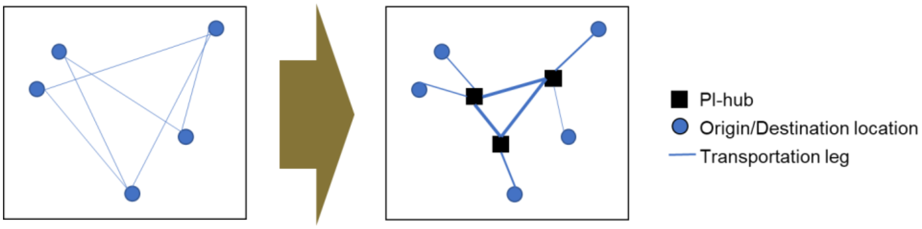

Figure 1:Illustrating regional modularization

2.4 Hierarchical Modularization

Hierarchical modularization is to divide delivery operations into multiple tiers which can be served in different time by different types of vehicle. It can be easily seen in the multi-tier or multi-echelon systems (Crainic & Montreuil, 2016; Winkenbach et al., 2016; Crainic et al, 2009; Smilowitz & Daganzo, 2007; Crainic et al, 2004). Montreuil et al. (2018) further developed the multi-tier system to hyperconnected delivery urban setting. Figure 2 describes 2-tier hierarchical modularization. The 2-tier system achieves better consolidation for tier 1, the delivery from fulfillment center to PI-hubs (which were urban consolidation centers (UCC) or satellite hubs in traditional settings). The tier 1 deliveries can be done during non-congested hours, overnight or early morning. The tier 2 delivery route is a lot shorter than tier 1 routes and carries smaller amount. Therefore, smaller vehicle or alternative transportation modes such as bicycle can be used depending on the scale. This is particularly beneficial when serving an area with special transportation restriction such as historical city center or when the road are very narrow inside a city as seen in many old cities. Generally speaking, higher tiers can utilize higher consolidation level and larger flow, which increases truck fillrate and shipping frequency in general. Lower tiers can adjust truck sizes to compensate relatively lower flow while maintaining shipping frequency.

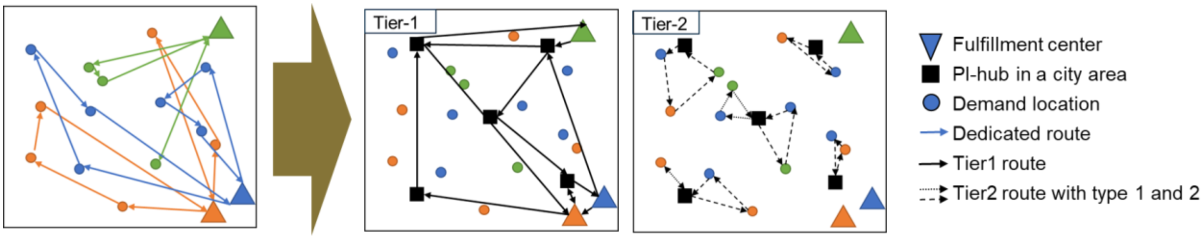

Figure 2: Illustrating hierarchical modularization

2.5 Functional modularization

Functional modularization is to divide multi-functionality routes into multiple routes of single functionality. This is less common than the other two types of modularization. Note that the in functional modularization, each functionality must require different resources which have different cost or require different time commitment. For example, pickup-and-delivery routes are common and proven to be more efficient than having pickup routes and delivery routes separately. Parragh et al. (2008) provides good survey of pickup and delivery literature and it is still actively studied in different context such as crowdsourcing (Arslan et al. 2019) or e-commerce distribution (Bergmann et al., 2020). The pickup and delivery are not the candidate of functional modularization as both requires same skillset of personal and same types of vehicles. Another multi-functionality route example is a route performing both physical item delivery and service at the same time. This route serves two functionality at once and it is a candidate of functional modularization. The two functionality require different time, equipment, and/or personnel. Note that Bask et al. (2010) pointed out that installation or recycling services can be bundled to the delivery as an additional value-added service module under e-commerce operations, as an example of *customer service* modularization which should be differentiated with the functional modularization presented here which is a *logistics service* modularization.

A more concrete example is a last mile delivery of furniture and large appliances, which often includes both delivery and installment (white-glove services) as described in Figure 3, which require different resources. Delivery requires large truck to fit the large items and a team of two personnel. Installment, on the other hand, can be done in small vehicle, but requires more skilled personnel and takes more time in general. When separated, installment routes can be served with small vehicle and delivery routes can be served without skilled personnel for installment. Also, installers can serve maintenance stops along with installation stops. Such functional modularization can increase efficiency by reducing the inefficient usage of more expensive resources, large trucks and skilled personnel. That is, each module can be more specialized.

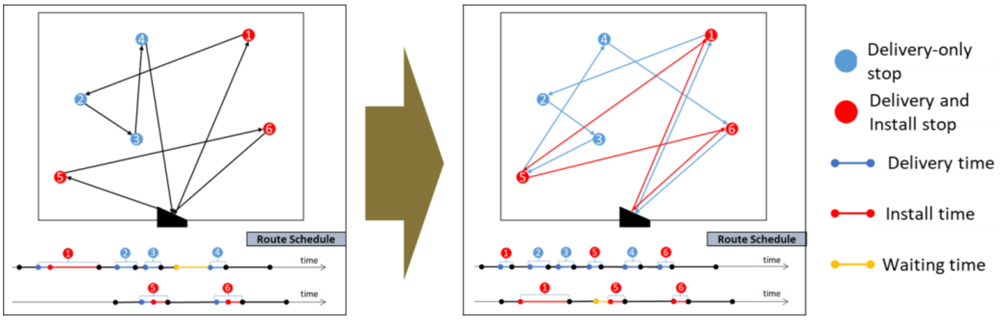

Figure 3: Illustrating functional modularization

3 Simulation-based experiment design

We designed a simulation-based experiment to measure the impact of hierarchical and functional modularization. The simulation experiment is built on the last-mile delivery of large items in a city. Here, we only briefly describe the scope of simulation and focus on the experiment design relative to the transportation modularization. See Kim et al. (2021) for details of base simulation platform structure.

3.1 Scope of simulation

The simulation experiment is built for the context of last-mile delivery of large items in urban area using the simulation platform presented by Kim et al. (2021) with customization. Urban delivery is suitable to implement the hierarchical modularization and large item delivery which often requires both delivery and installment can be a great example to implement the functional modularization.

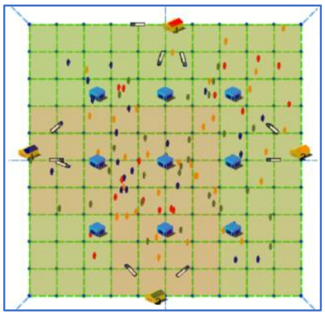

Figure 4 Simulation snapshot: four peri-urban fulfillment centers and nine PI hubs on a grid map

A grid-based model city is used where there are four retailers, each owns a single dedicated peri-urban fulfillment center (FC) and makes about 25 deliveries per day on average. When PI hubs are used, a network of nine PI hubs are assumed to be located in the city area. The snapshot of simulation with the 4 peri-urban FCs and 9 PI hubs are shown in Figure 4.

All stops involve delivery but only 80% of them requires installation. Each product has different delivery and installation times associate with it. Customers require a specific delivery time window between 9AM and 8PM, duration of which ranges from 2 to 4 hours. As pre-confirmation is needed for delivery time window, customers to be served on any day can be assumed to be known in advance without loss of generality.

3.2 Modularization scenarios

Two modularization schemes are used: hierarchical and functional modularization. For hierarchical modularization, current direct delivery (single-tier, ST) to customers from FCs and multi-tier delivery (MT) via PI hubs in the city are compared. In the latter, tier-1 delivery refers shipping from FCs to PI hubs and tier-2 from PI hubs to customers. For functional modularization, current multi-function delivery (MF) where delivery-only stops and delivery-and-install stops are mixed in a single route is compared to single-function delivery (SF) where each route performs either delivery or installation only. Four scenarios are constructed as shown in Figure 5: ST-MF, MT-MF, ST-SF, MT-SF.

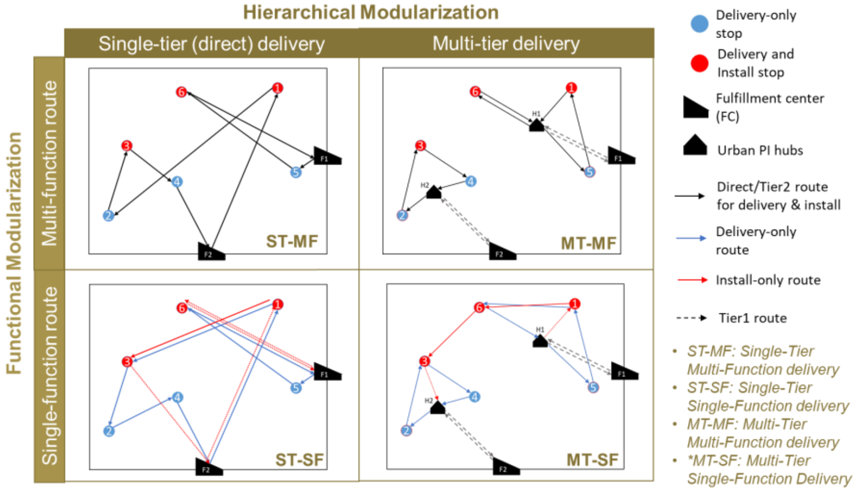

Figure 5: Four delivery scnenarios by hierarchical and functional modularization

Routes are served by different size of vehicles and have different requirement depending on tier and functionality. Table 1 summarizes the type of vehicles, labor requirements, and scheduling constraints for routes by tier and functionality.

Table 1: Transportation configuration by types of route with respect to hierarchical and funcational modularization

Functionality	Tier	Vehicle	Labor	Schedule
Delivery & install route	Direct delivery	17’ truck	Driver & Installer	Time window
	Tier-2	10’ truck	Driver & Installer	Time window
Delivery route	Tier-1	26’ truck	Driver	Overnight
	Direct delivery	17’ truck	2 Drivers	Time window
	Tier-2	10’ truck	2 Drivers	Time window
Install route	Tier-2	9' cargo van	Installer	Time window

Delivery routing problem in this case belongs to routing with time window and capacity constraints problem. Here, the routing heuristics in Kim et al. (2021) is used. However, they did not present the routing with functional modularization. The most critical constraint in this case is that installation cannot start before delivery is completed. Therefore, when delivery and installation routes are separated, delivery routes are first constructed with same heuristics to the mixed functionality routes where the expected time at each customer stop only include delivery time. Then, the expected finishing time of delivery at each customer, which then becomes expected earliest installation start time, is fed as an input for installation routing. When an installer may arrive before delivery team due to stochastic travel and service times in simulation, the installer waits until the delivery is completed. Note that, for installation routes, any size of cars can be used as they do not carry large products and it does not need to start from hubs or FCs unless specific tools need to be picked up at FCs. This means that an installer can park the installation vehicle at his/her place or anywhere preferred. To reflect the flexibility, it is assumed that installation routes are modeled as path, starting from nearest hub or FC and end at the last customer location. The associated costs for installation routes are also charged for the path only.

4 Experimental Results

This section presents the experimental results from simulation-based scenario analysis. The four scenarios (ST-MF, ST-SF, MT-MF, MT-MF) are evaluated on the urban delivery simulation, built on 8.5.1. University. The most important key performance indicator (KPI) is total operational costs. It consists of labor cost, vehicle rental cost, fuel cost and hub usage cost. As shown in Figure 6, the total operational cost is reduced with modularization. When soley applied, functional and hierarchical modularization reduces the average cost by 16% and 21% respectively. Together, up to 27% of operational cost savings is achieved.

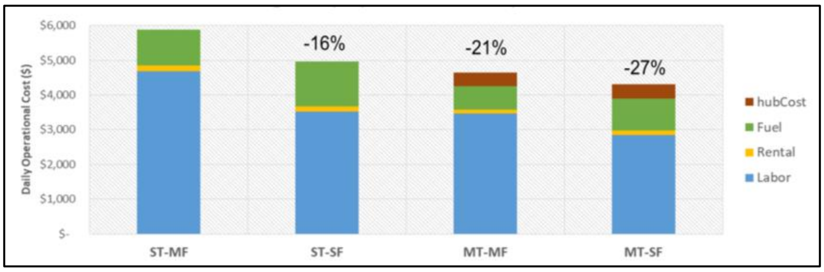

Figure 6: Average daily operational cost by scenario with percentage reduction

The average daily travel miles are shown in Figure 7. In fact, the functional modularization, increased the total travel miles due to the additional travel for installation. However, smaller, cheaper and more environmentally friendly vehicles used for installation routes make the cost increase not proportional to the travel mile. Similar impact is made with tier-2 routes. This also has indirect environmental and social impacts which is not measured explicitly in this paper.

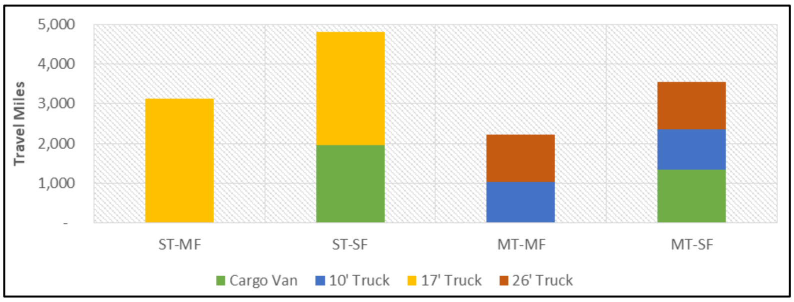

Figure 7: Average daily travel miles by vehicle type by scenario

Functional modularization, especially, changes labor requirement significantly. Figure 8 shows average daily labor hour by scenario, distinguished by types of personnel: driver and installer. Functional modularization reduces the labor hour of installers, who tend to have higher pay rate than drivers as they have more skillset. The total labor hours can also be saved with functional modularization by removing the waste of labor hour for 2-personnel team. Hierarchical modularization also has similar impact as tier-1 routes are served by a single driver with more consolidation.

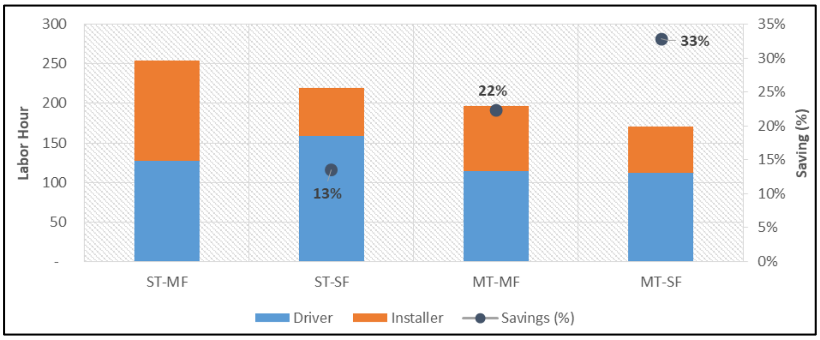

Figure 8: Average daily labor hour by type of personnel by scenario

5 Conclusion

This paper propose a concept of modularization of transportation and delivery in a hyperconnected logistics system. Three modularization schemes are described: regional, hierarchical and functional. All three types of transportation modularization have potential to facilitate dynamic consolidation, routing, and operation. The flexibility is especially beneficial in context of Physical Internet (PI) and multi-player operations. Modularized delivery and transportation better supports PI inspired hyperconnected logistics system while PI is also an enabler of transportation modularization. For example, PI containers can greatly reduce handling cost and complexity to justify the increased number of stops under modularized transportation. On the other hand, modularized transportation maximize the benefit of container operations. Then, the impact of hierarchical and functional modularization is demonstrated for the last mile delivery of furniture and large items. Simulation results shows that operational cost can be saved by 21% with hierarchical modularization and by 16% with functional modularization. Together, up to 27% savings can be achieved.

The paper opens various future research avenues by proposing an alternative transportation planning and operation scheme for more dynamic logistics system. Several limitations of the paper and future research topics are listed here. Firstly, rigorous mathematical routing and scheduling models and practical algorithms for each or any combination of the modularization scheme need to be developed. There are a few literature on regional or hierarchical modularization (Fazili et al., 2017; Ballot et al., 2012A; Crainic et al., 2009), but less literature exists on functional modularization or on combination. This is not only limited to routing problem. Integrated solution approach spanning a hub operations modeling or network design as well can generate more unbiased intuition. Secondly, the platform or system architecture which integrates the transportation and delivery modules needs to be designed thoroughly. A distributed platform structure can fit better than a single platform model especially under PI context which results in dynamic on-demand multi-player operations. Thirdly, digital and physical interface designs are crucial for modularized transportation. Digital interface needs to ensure the access to critical information such as destination information or arrival times for seamless operations while protecting confidentiality. Physical interface for the transportation modularization is PI hubs. Efficient facility design and use of PI containers can facilitate a smooth connection between modules. Forthly, the impact of modularization on multi-modal transportation system can also be a promising future research avenue. In such case, designing crossdocking or handling operation and capacity requirement measuring at multi-modal hubs as in Ballot et al. (2012B) can be a critical part of the study. Lastly, an extensive application to a real case study or actual implementation can better demonstrate the impact of modularized transportation.

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