

The following publication Z. Ouyang, Z. Yuan, Q. Chen, M. Li, Z. Zhao and G. Q. Huang, "Shipment Scheduling and Routing Protocols in Cyber-Physical Internet for Prefabricated Construction Modules Logistics" in IEEE Transactions on Intelligent Transportation Systems, 26(10), 16032-16046 is available at <https://doi.org/10.1109/TITS.2025.3581569>.

Shipment scheduling and routing protocols in Cyber-Physical Internet for prefabricated construction modules logistics

Zhiyuan Ouyang, Zhaolin Yuan, Qiqi Chen, Ming Li, Zhiheng Zhao, George Q. Huang*

Abstract—This paper explores the application of Cyber-physical Internet (CPI) in prefabricated construction logistics to enhance module shipment efficiency through a new scheduling framework. Drawing parallels between the TCP/IP model's data transmission process and the physical shipment of construction modules, the study identifies inefficiencies in current logistics practices, including obstructed information sharing and collaboration among practitioners. To address these challenges, the paper proposes a suite of CPI protocols, like the internet protocols, to standardize information sharing, scheduling & routing rules among logistics practitioners and nodes. Based on the CPI protocols, a hierarchical and decentralized shipment decision framework is proposed to govern how the routing decisions and shipment scheduling decisions are made at each logistics node. A set of numerical experiments is conducted based on a real-life shipment case of construction modules in the Greater Bay Area to exhibit the great efficiency and resilience of the proposed protocol-based decision framework. And a case study is designed to show how the proposed protocols influence the decision process. The study's contributions are threefold: demonstrating CPI application in a logistics scenario, developing protocols for efficient information sharing, and proposing a new decision framework for resilient and timely scheduling in complex logistics networks.

Index Terms—Cyber-physical Internet, dynamic freight routing, routing protocols, multimodal & multicriteria shipment

I. INTRODUCTION

The advent of modern internet enables fast and reliable transmission of data among innumerable devices used in any corner of the world. The great success of internet is mostly attributed to its openness, in which any device with a

network interface card can easily access it. The openness of the internet relies on a suite of well-designed protocols, which define a set of rules that users need to obey to communicate with it. Wherein, transmission control protocol and internet protocol (TCP/IP) model is the backbone of the modern internet, which defines how the data is processed at each internet node, like computer hosts and routers, to guarantee efficient information transmission between sending and receiving hosts [1]. The TCP/IP comprises of five layers, including application, transport, network, link, and physical layers. Data is firstly generated in the application layer and then segmented into several transmission units by the transport layer. The network layer determines the routing of data packets among routers and data packet transmission is performed by the link and physical layers. Such a data processing process in TCP/IP model provides us with important ideas to control the prefabricated construction module shipment in global logistics networks, because the shipment process is similar with data transmission process [2].

The module shipment is an important part of the prefabricated construction, which can comprise two transportation stages [3]. The produced modules are loaded into containers and shipped from factories to yards for temporal storage. Then, the stored modules are transported by trucks from prefabricated yards to construction sites for assembly at designated time. We can find several similarities between the module shipment and data packet transmission. (1) The factories, warehouses and construction sites are like computer hosts, which generate and receive physical “data”, i.e., the modules. (2) The standard containers can be regarded as data packets which segment the modules into several transportation units. (3) The transportation process among various logistics nodes are like the routing process of data packets. Nevertheless, the shipment of construction modules is actually more complicated than data transmission.

Zhiyuan Ouyang is with the Department of Logistics and Maritime Studies, the Hong Kong Polytechnic University, Hong Kong SAR.

Zhaolin Yuan is with the School of Intelligence Science and Technology, the University of Science and Technology Beijing,

Qiqi Chen, Ming Li, Zhiheng Zhao and George Q. Huang are with the Department of Industrial and Systems Engineering, the Hong Kong Polytechnic University, Hong Kong SAR.

Ming Li is additionally affiliated with Research Institute for Generative AI and Research Institute for Advanced Manufacturing, both at The Hong Kong Polytechnic University, Hung Hom, Hong Kong SAR

George Q. Huang is additionally affiliated with Research Institute for Advanced Manufacturing at The Hong Kong Polytechnic University, Hung Hom, Hong Kong SAR.

* Corresponding author: George Q. Huang
(e-mail: zhiyuan.ouyang@polyu.edu.hk (Zhiyuan Ouyang), yuanzhaolin@ustb.edu.cn (Zhaolin Yuan), qi-qi.chen@polyu.edu.hk (Qiqi Chen), ming.li@polyu.edu.hk (Ming Li), zhiheng.zhao@polyu.edu.hk (Zhiheng Zhao), gq.huang@polyu.edu.hk (George Q. Huang))

The module shipment process involves a lot of practitioners [4], like sending shippers, freight forwarders, carriers and receiving shippers. Close collaboration among them is required to guarantee punctual delivery of prefabricated modules. As so many decisions should be made in the shipment process, a planning, scheduling, and execution (PSE) framework is often generally to determine the decisions in a hierarchical manner [5]. The planning decisions include modules consolidation, container type selection and transportation mode selection. The scheduling decisions contain shipment consolidation, vehicle type selection, and traveling routes. The execution performs the above decisions according to the available resources.

The scheduling decisions are most important among them and exhibit three outstanding challenges, especially in those densely populated cities like Hong Kong and Singapore. First, just-in-time delivery is strongly desired as the buffer space of construction sites is limited. Early delivery can lead to additional cost while late delivery can delay the completion time. Second, construction modules are very bulky and heavy and there are some time constraints in truck type selection. It is not easy to match the dynamic transportations resources in multiple transportation modes with dynamic demands [6]. Third, various uncertainties and risks may occur during the module shipment process, like traffic congestion, equipment failure, supply shortage, insufficient capacity, or late delivery by upstream suppliers [7]. The original scheduling decisions could be no longer executable when these uncertainties and risks happen.

To address these challenges, a promising way is to apply some advanced technologies to realize informatization of the whole shipment process and information sharing among different practitioners. Recently, a novel idea was proposed by G. Q. Huang [8], namely Cyber-physical Internet (CPI). The CPI creates a "cyber layer" on top of the physical logistics network, which allows for the flow of construction modules in the physical domain to be sensed, configured, supervised, and optimized through the flow of information in the cyber space. Inspired by the mechanism of the internet, the CPI governs the shipment of module containers through designing a set of protocols, where the information format and scheduling rules for module containers are standardized among different logistics practitioners. Consequently, a logistics practitioner can efficiently share information and collaborate with others through connecting with the CPI, and the modules are transported efficiently just like transmitting data packers on the internet.

This paper aims to make a further exploration for the CPI based on prefabricated construction logistics, in which a new shipment scheduling framework facilitated by a set of CPI protocols will be proposed. Specifically, three research objectives will be achieved. First, a set of CPI protocols, like the internet and routing protocols, will be designed specifically to govern how the container information is shared among different logistics nodes and practitioners. Second, a group of decision tables, like routing tables on the internet, will be proposed to determine the routing, vehicle selection and departure sequence for module containers. Third, a list of

experiments will be conducted to exhibit the advantages of the protocol-based scheduling method and provide several management insights.

The contribution of this study is three-fold. Firstly, we give a demonstration on applying the CPI in a specific logistics scenario, which takes an important step from CPI conceptualization to CPI application. Secondly, we develop a suit of protocols to specify what information should be shared among CPI network nodes and what things should be done when new information is received. The protocols are fundamental components to facilitate goods transportation between sending and receiving shippers in the CPI network. Thirdly, we propose a new hierarchical and decentralized decision-making framework based on protocols to provide multi-objective shipment decisions. The proposed framework decomposes the complex shipment scheduling problem into a set of subproblems solved in a decentralized manner. The proposed framework also exhibits higher resilience and can achieve both lower cost and time module shipment compared with traditional static decision-making framework.

The rest of this paper is organized as follows. Relevant literature is reviewed in Section 2. The problem description on prefabricated construction module logistics and CPI network configuration are presented in Section 3. Section 4 presents CPI routing protocol and CPI shipment protocol. Numerical experiment setups and results are given in Section 5. Section 6 presents an application example of CPI based on a simple demonstration system. Section 7 closes this paper with a conclusion and a summary of some future research direction.

2. LITERATURE REVIEW

This study aims to develop a brand-new resilient scheduling decision framework based on a recently proposed technology (or new logistics paradigm), the CPI, to the just-in-time delivery for prefabricated construction modules. The relevant existing literature is reviewed from two perspectives, including technologies facilitating module shipment and module shipment decision methods.

A. Technologies facilitating module shipment

The module logistics is an important link of prefabricated construction, which directly influences if the desired modules are received just in time at construction sites. The prefabricated construction generally involves practitioners locating in different areas and module shipment may pass multiple logistics nodes with different transportation modes. Hence, just-in-time delivery cannot be achieved easily considering various uncertainties and risks may occur in this complex shipment process [9].

In recent years, a new generation of industrial technologies, like Building Internet of Things (IoT), Blockchain, Digital Twin and so on, has emerged to promote the transformation of the construction industry to intelligentization [10]. These advance technologies realize constant tracking of construction modules and real-time information sharing, which facilitate efficient collaboration among different practitioners and

alleviate the negative impact from uncertainties. Xu et al. [11] develop a cloud-based fleet management platform powered by IoT and cloud technology. A transportation management service sharing mechanism is innovated and integrated into this platform to collaborate involved stakeholders. Wang et al. [12] introduce a new blockchain-based information management framework for prefabricated construction supply chain to enhance on-time delivery of modules. A visualization system is then developed based on this framework to achieve (1) information sharing management, (2) real-time control of scheduling, and (3) information traceability. Lee & Lee [13] propose a digital twin framework for real-time logistics simulation, utilizing IoT sensors, BIM, and Geographic Information System (GIS). This framework can forecast potential logistics risks and accurately predict the arrival time of modules, thereby enabling effective coordination within the supply chain through reliable predictions. Most recently, Jang et al. [14] develop a cloud-based information system for automated transportation planning for construction modules, which can solve module logistics problems and improve the productivity of offsite construction assembly.

The technology introduced above focuses on eliminating information gaps among different logistics practitioners, which do not influence the conventional logistics procedure of construction modules. Nevertheless, a recently proposed concept, namely physical internet (PI), is intended to reform current logistics model [15]. The PI is identified as an open global logistics system referring to principles of computer network, including encapsulation, interfaces and protocols and so on, to transport physical goods in an efficient and sustainable way [16], [17], [18]. The core concept of PI is to standardize and share all logistics physical facilities, like containers, load transfer, logistics hub, transportation vehicles, to establish an interconnected logistics network [19]. Some studies have demonstrated how the PI can be adopted in prefabricated construction. For example, Zhong et al. [20] propose architecture of an PI-enabled prefabricated housing construction to seamlessly integrate the logistics echelons with a PI-enabled decision support system. Chen et al. [21] develop a PI-enabled Building Information Modelling System integrating Auto-ID technologies, building information modelling, and cloud computing. The system enables real-time collection, communication, and visualization of information across the processes of production, transportation, and on-site assembly. Most recently, Achamrah et al. [22] propose a dynamic and reactive routing protocol for a PI sub-network to guarantee consistent connectivity among PI nodes when uncertainties and disruptions exist. Sun et al. [23] further develop an information-sharing policy for PI routing protocols to ensure privacy-protecting data sharing in PI networks.

Nevertheless, the conventional decision framework based on centralized optimization model is generally used in PI-related research, which cannot fully utilize the advantage of logistics facility standardization [24]. Recently, the cyber-physical internet (CPI) is proposed, which aims to reform the decision-making process of logistics system powered by PI by adding a cyber space to completely map the physical logistics network

to a digital logistics network [25], [26]. The cyber space of CPI fully inherits the features and merits of computer network, enabling all physical logistics entities to be digitally connected and shipment decisions can be made in a computer network manner based on a suit of protocols like transmission control protocol (TCP). Wu et al. [27] propose a bottom-up approach to integrate the logistics infrastructure in the CPI environment by referring to the conceptual fusion of computer network. Qu et al. [28] design a routing table and routing protocol for the CPI and apply them in a B2B e-commerce logistics scenario to reduce the shipment time or cost. Ng et al. [29] develop a CPI routing protocol for the modular integrated construction logistics to record the carbon footprints along the logistics networks. The above two studies take a pioneering step to explore how freight is transported in the CPI network in a computer-network way. Most recently, Yuan et al. [30] propose a set of protocols for the CPI to govern how the shipment units (containers) are generated for modular integrated construction logistics. The generation process of shipment unit in this work is designed by referring to the transmission control protocol (TCP) in computer network. Nevertheless, current research in the field of PI or CPI only addresses routing decisions with a single objective, i.e., cost, time or carbon emissions. Problems relating to transportation resources assignment, routing selection and scheduling with multiple objectives in a multi-modality logistics network are still unsolved.

B. Decision framework in module shipment

Above advanced technologies enable optimal shipment scheduling decisions of construction modules are made based in real-time. However, the current decision framework is generally based on optimization model, like integer linear model, and (exact or heuristic) optimization algorithms [4]. Hsu et al. [31] propose an optimization model based on two-stage stochastic programming for logistics processes considering three tiers of operation: manufacturing, storage and assembly. This model can handle uncertain demands from construction sites and determine the reaction of module manufacturing and inventory to the demand variations. Fang & Ng [32] use a genetic algorithm to optimize the logistics of precast components from module factory to intermediate warehouse (yard) and finally to construction site, where the production schedule, delivery schedule and material storage are considered.

Recently, Hsu et al. [33] develop a multi-stage stochastic programming model to seek the optimal supply chain configuration for the prefabricated module construction. In this model, several operation decisions, including production, transportation and inventory plans, are made at multiple time points. Karam & Reinau [34] propose a real-time decision framework to handle unexpected disruption in road transport cause by extreme weather, traffic accidents and so on. This framework combines a simulation model, optimization algorithms, and a cost-effectiveness analysis to handle the disruptions by re-planning shipment trips. H. Wang et al. [35] formulate an integer programming model to minimize the total transportation costs, comprising of trailer rental, fuel cost and

worker salaries. This model is evaluated based on a case study in Hong Kong, and 58.7% transportation cost reduction is obtained compared with conventional delivery strategy. Larsen et al. [36] study an integrated problems of routing containers and vehicles in a multimodal transportation network. A co-planning method under the synchromodal decision framework is developed to collaborate the transport plans between a logistics service provider and a flexible service operator.

The near optimal shipment decisions can be obtained by using the above optimization models. However, this generally requires a centralized decision framework to make integrated decisions at a system level. The integrated optimization model can be complex as the logistics process involves a lot of practitioners, leading to that seeking the global optimal decisions is very difficult. Larsen et al. [36] attempt to determine the containers and vehicles' routing decisions in a decentralized manner. However, the decentralized degree is not enough, leading to large problem scale for logistics service providers in complex transportation networks. Meanwhile, the decision framework based on integrated optimization model exhibits a lowly resilient performance for those non-stationary accidents. The decision framework proposed by Karam & Reinau [34] can handle uncertainties but it requires system-level information and only support land transportation mode. In contrast, computer network demonstrates strong resilience towards various uncertainties, like signal fluctuation, changes in connection status and network congestion. Inspired by the transmission control of data packets in computer network, this study is going to develop a brand-new decision framework based on protocols in the CPI to make shipment decisions for construction modules in a dynamic, decentralized and hierarchical manner.

3. CPI-BASED DECISION FRAMEWORK FOR PREFABRICATED CONSTRUCTION MODULES LOGISTICSS

In this section, we firstly introduce the background of prefabricated construction modules logistics and describe the problems involved in this logistics scenario. Subsequently, a CPI network is constructed for the logistics system of prefabricated construction modules. Finally, a hierarchical and decentralized decision framework based on the CPI is proposed to achieve resilient control of module shipment.

A. Prefabricated construction modules logistics

Prefabricated construction modules logistics is a classic logistics scenario where produced construction modules are transported from a factory to a building in construction site. This logistics scenario has two salient features. The first one is that truckload consolidation is not required because construction modules are large and bulky. Another one is that the required modules should be delivered to the right place at the right time. Early arrival of modules leads to no sufficient buffer space for storing the modules while late arrival causes extension on makespan. To facilitate spatial-temporal synchronization, the produced modules can be transported to a prefabricated yard in advance. The prefabricated yard is located

in the same city as the construction site, so that the modules stored in the yard can be quickly sent to the site once they are in need.

Prefabricated construction modules logistics is a complicated process involving many logistics practitioners and multiple transportation modes. Hence, there are many decisions to be determined, including order consolidation, picking, sorting & loading, shipment mode selection, shipment routing and so on. Generally, each practitioner makes the corresponding decisions independently, which lacks sufficient information sharing among them and cannot efficiently manage shipment uncertainties. To better achieve the synchronization objective of prefabricated construction modules logistics, a hierarchical and decentralized decision framework based on the CPI is proposed. Before introducing this decision framework, we firstly demonstrate how to configure a CPI network for a specific logistics scenario of prefabricated construction modules.

B. CPI network configuration

We refer to a classic scenario of prefabricated construction modules logistics to interpret the principles of CPI (see **Fig. 1**). In this logistics scenario, three categories of logistics practitioners are considered, including industrial park, prefabricated yard, and construction site. The industrial park locates in Mainland China and comprises of several module factories. All produced modules are consolidated and packed with standardized containers at the factories. These containers are subsequently shipped to a logistics hub in the industrial park for further consolidation and transshipping. The logistics hub supports both land and sea transportation modes. Once the containers are dispatched from the logistics hub, they can be transported to construction sites directly or to a prefabricated yard in Hong Kong. The prefabricated yard is a transit center for construction modules and a supports multiple transportation mode.



Fig. 1. Locations of construction modules logistics facilities.

Given the logistics scenario introduced above, we can construct a CPI network by defining network components in the logistics system (see **Fig. 2**). The basic one is CPI host, which is defined as a terminal entity sending and receiving physical goods and their digital data. Therefore, factories, yard storage areas and buildings are CPI hosts. Like computer networks, the transmission unit in the CPI is standardized, called protocol

shipment unit (PSU). From the digital perspective, a PSU is a standardized data packet. While from the physical perspective, a PSU is a standardized holder such as 20ft or 40ft containers. The PSU transmission between two CPI hosts can pass through multiple CPI routers. As a PSU has digital and physical attributes, a CPI router is a device like a common router to transfer the digital PSUs. Meanwhile, a CPI router is defined as an area for cross-docking and transferring physical PSUs, so that logistics hub yard dock area and site receiving area are CPI routers. Like computer networks, the network mentioned in **Fig. 2** is defined as a CPI wide area network (WAN). All CPI hosts can be further brought into different CPI local area networks (LAN) according to the CPI routers that they connect. Based on the four affiliated LAN, each CPI host or router port is given to a physical internet protocol (PIP) address like the internet protocol (IP) address in computer network.

Once the CPI is configured, the construction modules can be shipped by imitating data packet transmission in the computer network with Transmission Control Protocol/Internet Protocol (TCP/IP) model. The TCP/IP model is a suite of communication protocols used to interconnect network devices, which can guarantee reliable, efficient, and robust data transmission among hosts. The success of TCP/IP model is derived from data segmentation, hierarchical and decentralized processing of data packets. The TCP/IP constitutes five layers, i.e., application, transport, network, link, and physical layers, which independently perform their functions to process data packets based on predetermined protocols. However, the CPI involves transmission of physical items, which contains a series of complex decisions and operations in the physical world. The TCP/IP model of digital internet, obviously, cannot be directly applied in the CPI. Therefore, we define a new suite of shipment protocols, namely Transportation Control Protocol/Physical Internet Protocols (TCP/PIP) model for governing the PSU shipment in the CPI.

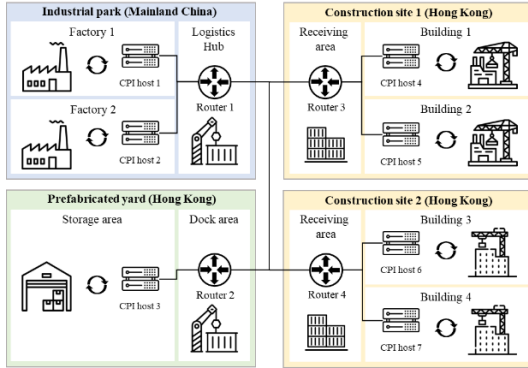


Fig. 2. CPI network for the logistics of prefabricated construction modules.

C. Transmission Control Protocol/Physical Internet Protocol-based decision framework

The hierarchical and decentralized methods on information sharing and data packets processing of TCP/IP model provide us with valuable ideas to develop an efficient decision framework on construction modules shipments. Therefore, we propose a decision framework based on TCP/PIP model for CPI network to control the shipment of PSUs. The TCP/PIP model

has five layers, including application, transport, network, link, and twin layers. The first four layers, i.e., from application layer to link layer, work in cyber space, which digitally make shipment PSE decisions. The bottom twin layer works in both cyber and physical space, which is responsible for the enforcement of the above decisions and transmission of PSUs when all required resources are ready (**Fig. 3**).

Application layer: this layer does not involve any shipment decisions and is contained only in CPI hosts. As a sending shipper, this layer is used to digitally generate data of logistics orders. As a receiving shipper, it checks the received modules.

Transport layer: this layer only works in CPI hosts, making shipment planning decisions [30]. Given logistics orders dynamically outputted by the Application layer, the Transport layer make decisions after every H . By doing so, it firstly makes order consolidation decisions to select the logistics orders that should be fulfilled in the future H time. Based on the item types in the selected orders, the type of PSU is determined, followed by making space allocation and PSU loading decisions. Hence, we can know which items in the selected orders should be loaded in which PSU with what type, and how these items are loaded. Once the PSUs are generated, the PSU dispatching time is optimized to guarantee the orders in PSUs are received in expected time. The Transport layer outputs a set of digital data packets with a CPI TCP header, a TCP header includes information shared to the next CPI host like PSU type, PSU ID, Orders' IDs and loading status.

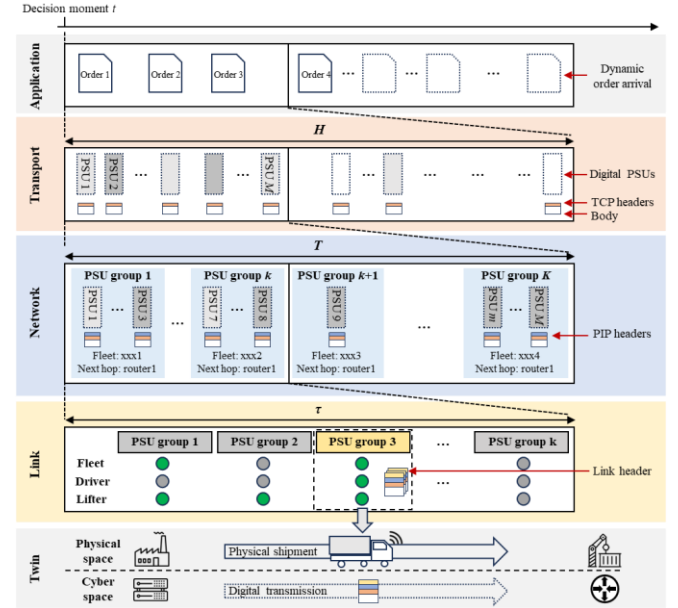


Fig. 3. Workflow of CPI five-layer model

Network layer: this layer works in CPI hosts and routers. It takes the output of Transport layer as the input to make scheduling decisions for PSU shipment with decision period T ($T < H$). The decisions include shipment mode and the next hop selection of each PSU, and PSU consolidation, where each PSU group is matched with a specific transportation resource with an actual dispatching time. The Network layer of a CPI host or router encapsulates a PIP header for each PSU, which contains all information shared to the Network layer of other

CPI hosts and routers. A PIP header not only includes source & destination addresses, but also contains remaining time & cost to the destination and metric preference, which influence the routing selection in the next CPI node (router).

Link layer: this layer makes execution decisions of PSUs with a short decision period τ ($\tau < T$) and is involved in all CPI hosts and routers. The Link layer digitally matches tractor fleet, tractor, and drivers for each PSU, and then resolves the Media Access Control (MAC) address of the next hop. A link head is finally added on the top of PIP head, which contains source and destination MAC addresses.

Twin layer: this layer corresponds to the physical layer of TCP/IP model, which is responsible for the actual shipment of units. Nevertheless, the Twin layer works in both cyber and physical space. On the one hand, it physically transports units by performing PSE decisions. On the other hand, the transportation status is sensed by the sensors on the tractor, and its digital twin can be established and traced in the cyber layer. The transmission medium for digital PSUs is internet. While for physical PSUs, the transmission medium includes roads, rivers, and so on, depending on the shipment mode.

4. PROTOCOL-BASED SHIPMENT SCHEDULING AND ROUTING

In this section, we explain the workflow of Network layer in detail. As mentioned above, the Network layer at each node (host or router) is designed to make scheduling decisions on the PSUs output by the Transport layer [30], including routing, consolidation, and dispatching decisions at hosts and routers. The primary objective of making these decisions is to ensure the PSU shipment requirements on time and cost are satisfied. Hence, a multi-level and decentralized scheduling decision method is proposed in the Network layer, which is visually illustrated in **Fig. 4**. The inputs of the Network layer are a set of PSUs with TCP headers obtained at a scheduling time t in a node j (host or router), denoted as $I_{t,j}$. For each PSU i ($i \in I_{t,j}$), a set of information for each PSU is known in advance, including the PSU receiving time t_i , source PIP address p_i^{sou} , destination PIP address p_i^{des} , expected departure time t_i , required time to destination t_i^{des} , required cost to destination c_i^{des} , PSU type o_i^{psu} and metric preference α_i . The t_i^{des} and c_i^{des} in a PSU respectively indicate the required time and cost that spent by shipping this PSU from current node j to the destination, which are initialized by the Transport layer and dynamically updated when this PSU arrives to a new router. Metric preference α_i ($\alpha_i \in (0,1)$) is a parameter determined by Transport layer, $\alpha_i = 0$ means shipment modes with lower cost are preferred, $\alpha_i = 1$, otherwise.

Given the inputs, the Network layer firstly determines the PIP address of the next hop of each PSU (p_i^{next}) by running a next hop selection algorithm based on a routing table R_j^{route} , c_i^{des} and t_i^{des} . The routing table $R_j^{route} = \{r_{j,1}^{route}, r_{j,2}^{route}, \dots, r_{j,N}^{route}\}$ comprises of N entries, and each entry indicate a next hop with pareto optimality in terms of shipment cost and time from j th node to a specific network destination. The routing table R_j^{route} is dynamically updated by a CPI routing protocol which controls the information sharing with directly connected

routers. With the next hops of all PSUs at time t , i.e., $\{p_i^{next}\}_{i \in I_{t,j}}$, the PSU consolidation decisions and dispatching decisions are subsequently made by referring an capability table R_j^{cpb} and solving a PSU dispatching problem. The R_j^{cpb} records all currently available transportation resources at the node j . This table is dynamically updated according to available transportation resources provided by the freight forwarders or carriers, which helps to efficiently match logistics service supplies and demands among various logistics practitioners. Overall, the Network layer outputs PSUs with PIP headers and scheduling decisions on the PSUs. The four key components in this layer are routing table, next hop selection, capability table and PSU dispatching model.

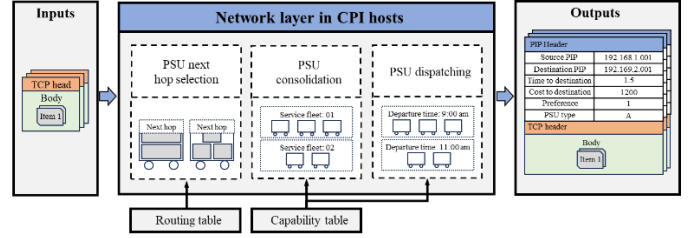


Fig. 4. Protocol-based shipment scheduling in the Network layer of CPI

A. CPI routing table and next hop selection

Being similar to the routing table in the computer network, the CPI routing table R_j^{route} lists the next hop to specific CPI networks destinations from the node j . We denote a set P_j^{route} comprising of all next hops stored in R_j^{route} . Table 1 gives an example on routing tables stored in host 1. $r_{j,n}^{route}$ ($n = 1, 2, \dots, N$) records five types of information, including ID number, network destination/netmask, transportation mode, next hop, and metrics.

There are three differences between conventional routing table and CPI routing table. First, CPI routing table records transportation mode considering the multiple transportation mode to the next hop. Second, unlike the computer network focusing on transmitting data packets as soon as possible, the CPI network needs to consider the shipment cost and time. There are two important criteria considered in most logistics scenarios. The CPI routing table evaluates the smallest “cost” of using the indicated route with a group of metrics including unit cost and shipment time. Once the shipment time of the optimal routes is known, just-in-time delivery of modules can be achieved by appropriately determining the actual departure time and shipment routes. Third, given a destination and the shipment mode selected at a CPI router or host, multiple metric groups are demonstrated (see entries 02-03 in **Table 1**). These metric groups are pareto optimal in terms of unit cost and shipment time to corresponding destinations. **Fig. 5** gives a demonstration on Pareto optimal routes.

The computer network adopts the longest prefix match algorithm to select a unique entry $r_{j,\tilde{n}}^{route}$ from a routing table R_j^{route} . Such an algorithm cannot be used in the CPI network because one network destination can correspond to a set of entries $\tilde{R}_j^{route}$ ($\tilde{R}_j^{route} \subseteq R_j^{route}$) (see entries 02 and 03 in Table 1). In this case, another set of entries $\tilde{R}_j^{route}$ ($\tilde{R}_j^{route} \subseteq R_j^{route}$) is

firstly obtained by filtering $\bar{R}_j^{route}$ according to their metrics to satisfy the time & cost requirements of PSUs. Then, a next hop selection algorithm (see **Appendix A**) is used to exactly select an entry from $\bar{R}_j^{route}$ given the $(p_i^{des}, c_i^{des}, t_i^{des}, o_i^{psu}, \alpha_i)$ of a PSU.

Table 1. An illustrative CPI routing table for Router 1.

ID	Network destination / Netmask	Mode	Next hop	Metric/ Unit (USD/ day)
01	001.001.01.002/32	Land	001.001.01.002	50, 0.1
02	001.001.03.0/24	Land	001.001.07.001	1000, 1
03	001.001.03.0/24	Sea	001.001.06.001	700, 3.5

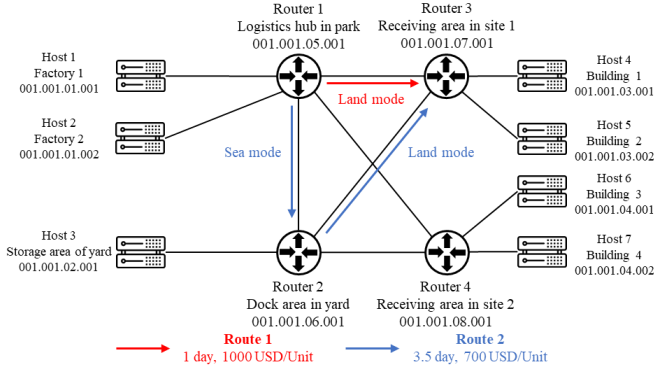


Fig. 5. Two pareto optimal routes from Router 1 to Router 3 in the illustrative instance

B. CPI capability table and PSU dispatching scheduling

Computer network transmits data packets through fibre-optic cables, in which data packets can actively “move”. In the CPI network, however, the physical part of PSUs cannot “move” by themselves. The shipment of physical PSUs in the CPI network requires transportation resources, such as truck, train. Therefore, a capability table R_j^{cpb} is stored at a CPI host or router, which formats and lists all available transportation resources.

The R_j^{cpb} consists of eight items, which respectively records ID number k ($k \in K_{t,j}$), next hop address p_k^{cpb} , shipment mode q_k^{cpb} , capacity Q_k^{cpb} , price m_k^{cpb} , available time window (e_k^{cpb}, l_k^{cpb}) and supporting PSU type o_k^{cpb} . The R_j^{cpb} are dynamically updated based on the information provided by the freight forwarders or carriers. When the next hops of all PSUs are determined, the shipment demands at each CPI host and routers are revealed. Meanwhile, the transportation resources will be assigned to each PSUs based on the PSU shipment requirements. **Table 2** gives an example of R_j^{cpb} .

Table 2. An illustrative CPI capability table for Router 1

ID	Next hop	Mode	Cap.	Price	Time window	PSU
01	001.001.07.001	Land	1 Unit	50	01/06 12:00 02/06 12:00	A,B
02	001.001.06.001	Land	5 Unit	950	03/06 13:00 04/06 10:00	B
03	001.001.06.001	Sea	50 Unit	210	05/06 13:00 06/06 13:00	B

At a scheduling time t ($t = 0, T, 2T, \dots$), a PSU dispatching problem is solved to exactly determine how the transportation

resources in the R_j^{cpb} are assigned to each PSU in $I_{t,j}$. Given a specific next hop and transportation mode p^* and q^* , we assume $\tilde{R}_j^{cpb}$ is a subset of R_j^{cpb} containing all entries whose $p_k^{cpb} = p^*$ and $q_k^{cpb} = q^*$. Meanwhile, a PSU subset $\tilde{I}_{t,j} = \{i \in I_{t,j} : p_i^{next} = p^*, q_i^{next} = q^*\}$ indicates all PSUs whose next hop and transportation mode is p^* and q^* . We define a set of decision variables $x_{i,k}$ ($x_{i,k} \in [0,1]$, $i \in \tilde{I}_{t,j}$, $k \in \tilde{R}_j^{ava}$), where $x_{i,k} = 1$ means the k th transportation resources in $\tilde{R}_j^{ava}$ will be allocated to the PSU i in $\tilde{I}_{t,j}$. We further define t_k^{fleet} represents the expected departure time of fleet k from CPI host j . Therefore, the PSU dispatching problem in node i for the next hop p^* and transportation mode q^* at scheduling time t can be formulated as:

Problem 1:

$$\text{Min} \sum_{i \in \tilde{I}_{t,j}} \sum_{k \in \tilde{R}_j^{cpb}} x_{i,k} \cdot |t_k^{fleet} - t_i| \quad (1)$$

Subject to:

$$\sum_{k \in \tilde{R}_j^{ava}} x_{i,k} \leq 1, \forall i \in \tilde{I}_{t,j} \quad (2)$$

$$x_{i,k} \cdot f^+(o_i^{psu}, o_k^{cpb}) = 0, \forall i \in \tilde{I}_{t,j}, \forall k \in \tilde{R}_j^{cpb} \quad (3)$$

$$\sum_{i \in \tilde{I}_{t,j}} x_{i,k} \leq Q_k^{cpb}, \forall k \in \tilde{R}_j^{ava} \quad (4)$$

$$e_k^{cpb} \leq t_k^{fleet} \leq l_k^{cpb} \quad (5)$$

where the objective function is to minimize the total time difference between actual departure time t_k^{fleet} and PSU expect departure time t_i , at scheduling time t . In other words, we hope the PSUs received at the CPI node j can be sent to the next hop as planned by the Transport layer. Constraint (2) guarantees that each PSU is served by one vehicle group at the most. Constraint (3) means that the type of each PSU should be supported by the assigned fleet, where the function $f^+(o_i^{psu}, o_k^{cpb})$ outputs 1 if the intersection between c_i^{psu} and c_k^{cpb} is an empty set, otherwise it output 0. Constraint (4) ensures the capacity of each vehicle group is not surpassed. Constraint (5) limits each fleet is used within the available time window.

C. CPI routing protocols and PIP header update

The transportation resources, shipment cost and shipment time between any two points keeps changing with time. The CPI network can capture these alterations through dynamically updating the above two tables. The update of R_j^{cpb} is straightforward, which relies on the transportation information revealed by freight forwarders and carriers. The update of R_j^{route} is controlled by CPI routing protocols, which works by referring to the internet routing protocols. In a computer network, the routing table in a router can be renewed by receiving formatted information (routing tables) from the directly connected routers. With the shared information, this router knows which destinations it can reach though passing the adjacent routers. Therefore, after several rounds of information sharing, a routing table will be generated to record the next hop to all network destinations.

The CPI routing protocols work in a similar way but should further consider the features involved in the construction

modular logistics, including multiple next hops with Pareto optimal and multi transportation modes. The shared information between CPI routers is a set of aggregated routing tables R_j^{agg} , which merge the entries according to the destinations and discard the information in transportation mode and next hop. During this aggregation, only the Pareto optimal metrics in an entry to a destination will be preserved. **Table 3** give an illustrative sample on R_j^{agg} of node B shared to node A. The reason of making this aggregation is that the transportation mode and next hop is useless as the node A does not care about how the PSUs are transported in node B. Node A only cares how much cost and time it will take when the PSUs arrive to the node B, which determines whether the node B is set as the next hop in node A to a destination.

Table 3. An illustrative aggregated routing table shared from Router 1 to Router 2

ID	Network destination / Netmask	Metric (USD/unit, day)
01	001.001.01.001/32	50, 0.1
02	001.001.03.0/24	1000, 1; 700, 3.5

Given an aggregated routing table R_j^{agg} to a CPI node j , the R_j^{route} is updated by a CPI routing table update algorithm (see **Algorithm 1**). When a node j receives the R_j^{agg} from node j' , it get several new entries R_j^{new} and know it can get to some other destinations through router j' . If a destination is not recorded in current routing table R_j^{route} , it will be directly added to the R_j^{route} . If it is already recorded in current routing table, the node j will firstly update the entries originating from the node j' and then remove and replace those entries being dominated by new entries. An entry in the routing table may contain multiple metrics, the comparison between two entries A and B with multiple metrics obeys following two rules. (1) if a metric exists in entry A dominates the first metric of entry B, we denote the first metric of entry B is dominated by entry A. (2) if all metrics of entry B are dominated by entry A, we conclude that the entry B is dominated by entry A. For example, entry A has one metric (800,1) and entry B has two metrics {(600,1) (850 0.8)}, then entry A is dominated by entry B. However, if A has two metric {(800,1) (500,1.2)}, entry A and B do not dominate each other.

The initial routing table in a CPI node only involves routing information to the directly connected routers, where the shipment time can be obtained by real-time and historical shipment data and the shipment cost is obtained based on the transportation quotation provided by carriers or freight forwarders in the capability table. Each CPI node frequently shares its routing table to the adjacent nodes so that the cost and time information in the whole CPI network is revealed in routing tables in real time. The optimal shipment decisions satisfying customers' demands can be dynamically made by referring to the CPI routing tables.

Algorithm 1: CPI routing table update algorithm

Inputs: R_j^{agg} , R_j^{route}
Outputs: R_j^{route}

```

1 for each entry  $r_{j,n}^{agg}$  in  $R_j^{agg}$ 
2 if the destination of  $r_{j,n}^{agg}$  is not contained in  $R_j^{route}$ 
2   Get new entries  $R_j^{new}$  based on  $r_{j,n}^{agg}$  and  $R_j^{route}$ ;
3   Add new entries  $R_j^{new}$  to  $R_j^{route}$ ;
4 else
5   Denote all entries having the same destination with  $r_{j,n}^{agg}$  as  $\bar{R}_j^{route}$ ;
6   Get new entries  $R_j^{new}$  based on  $r_{j,n}^{agg}$  and  $R_j^{route}$ ;
7   for each new entry in  $R_j^{new}$ 
8     for each entry  $\bar{r}_{j,n}^{route}$  in  $\bar{R}_j^{route}$ 
9       if  $\bar{r}_{j,n}^{route}$  originates from router  $j'$ 
10        Update metrics of  $\bar{r}_{j,n}^{route}$  according to metrics of  $r_{j,n}^{new}$ ;
11      else
12        Compare metrics of  $r_{j,n}^{new}$  with metrics of  $\bar{r}_{j,n}^{route}$ 
13        if metrics of  $r_{j,n}^{new}$  dominate metrics of  $\bar{r}_{j,n}^{route}$ 
14          Remove  $\bar{r}_{j,n}^{route}$  from  $R_j^{route}$ 
15        end if
16      end if
17    if metrics  $r_{j,n}^{new}$  is not dominated by any metrics in  $\bar{R}_j^{route}$ ;
18      Add new entries  $r_{j,n}^{new}$  to  $R_j^{route}$ ;
19    end if
20  end for
21 end for

```

5. NUMERICAL STUDY

In this section, we introduce a numerical case inspired by practical delivery instances of prefabricated construction modules in Hong Kong (see the Reference Material on Logistics and Transport for Modular Integrated Construction Projects, 2020). This case considers two construction sites respectively locating in the Kwun Tong and the Central & Western Districts of Hong Kong. Each construction site has two buildings constructed though prefabricated modular assembly. There is a module factory with two mold tables in the Nansha District, Guangzhou. The produced modules can be directly shipped to the above two construction sites for assembly or shipped to a prefabricated yard in Yuen Long District, Hong Kong for temporal storage. The shipment between factory and prefabricated yard can be executed in both land and sea modes.

From the CPI perspective, the factory, prefabricated yard and construction sites introduced above are CPI LANs, where each of them contains one CPI router and several CPI hosts. Meanwhile, three CPI routers are also deployed at logistics transferring nodes, i.e., freight terminals. The layout of all CPI hosts and routers are shown in **Fig. 6**. The settings on PIP address, container type, tractor type and traveling time & cost are shown in **Appendix B**.



Fig. 6. Layout of CPI hosts and routers in Greater Bay Area

The shipment scheduling period T is set to 3 days, meaning that the accumulated PSUs to be shipped in future 3 days are scheduled at each decision moment. This involves several steps at each CPI node as mentioned in Section 4: (1) Update the capability table. (2) Update routing tables. (3) Determine the next hops for PSUs. (4) solve the PSU dispatching problem. We assume the decision time t starts from 0 and the PSUs received with time at each CPI host are shown in **Appendix C**. At a decision moment t , the transportation resources in each CPI node are randomly generated in terms of destinations, the number of fleets, the number of tractors in each fleet, tractor type and available time window. The number of fleets $|K_{i,j}|$ is assumed to obey Poisson distribution with a mean value of 5. The number of tractors in each fleet is set to be 1, 2 or 3 with identical probability. The destination is generated based on the directly connected routers with identical probability. e_k^{cpb} for a fleet is equal to its generation time plus a random variable obeying uniform distribution [0 day, 7 days] and l_k^{cpb} for a fleet is equal to its e_k^{cpb} plus a random variable obeying uniform distribution [1 day, 3 days]. This setting means that we can know an available transportation in 7 days at the most. The delivery resources could be insufficient, and some PSUs will be postponed to the next decision moment in this case.

A. Results in PSU routing

In a CPI network, the routing decisions for PSUs are determined by referring to routing tables in CPI nodes. As both shipment time and cost are considered for routing, there are multiple optimal routes that may exist between two destinations. **Table 4** tabulates all Pareto optimal routing decisions between CPI LANs in the instance introduced above. And **Fig. 7** visually depicts the Pareto shipment routes departing from router R1. We can find that there is only one optimal route between R1 and R4, R4 and R5, R4 and R7. Nevertheless, when shipping a PSU from R1 to R6, the routing choices are diverse, which mixes both land and sea transportation modes and exhibits different superiority in shipment cost and time. The route R1-R4-R6 is the most time-saving choice, which only takes 0.45 days by using the land transportation mode and transfers once at R4. The routes R1-R2-R3-R6 and R1-R2-R5-R6 involve water-land-intermodal transportation, which respectively saves 50 and 200 dollars cost but also lead to 1.75- and 2.7-days additional transportation time. Similar routing choices are observed when a PSU is transported from R1 to R7.

Table 5 and **Table 6** respectively show the routing table stored in host H1 and Router R3. As the host H1 only connects with R1 (192.168.1.003), the next hops of all PSUs generated in H1 are R1 no matter where the destination is. We can find multiple metrics stored in different entries of **Table 5**, so that the sending shipper can know whether the PSUs can be transported to designated destinations in advance given the required cost and time. As observed in **Table 6**, a set of Pareto optimal next hops with different transportation modes could be stored for one destination. Each PSU can select the transportation mode and next hop according to the cost requirement c_i^{des} , time requirements t_i^{des} and when it metric preference o_i^{psu} when it arrives to the CPI router R3.

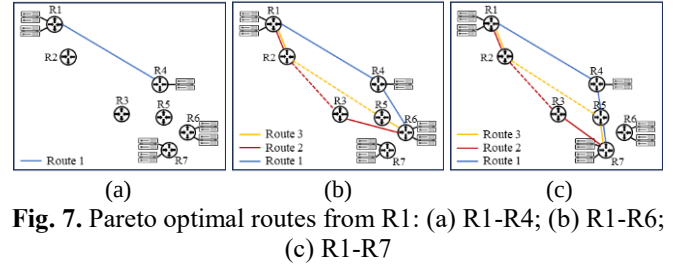


Fig. 7. Pareto optimal routes from R1: (a) R1-R4; (b) R1-R6; (c) R1-R7

Table 4. Pareto optimal shipment routeing decisions

Origin Network, Destination Network	Routes	Metrics
192.168.1.0/24, 192.169.1.0/24	R1-R4	300, 0.30
192.168.1.0/24, 192.169.4.0/24	R1-R4-R6	700, 0.45
	R1-R2-R3-R6	650, 2.20
	R1-R2-R5-R6	500, 3.15
192.168.1.0/24, 192.169.5.0/24	R1-R4-R4-R7	800, 0.50
	R1-R2-R3-R7	500, 3.15
	R1-R2-R5-R7	500, 3.15
192.169.1.0/24, 192.169.4.0/24	R4-R6	400, 0.15
192.169.1.0/24, 192.169.5.0/24	R4-R5-R7	500, 0.20

Table 5. Routing table in H1

ID	Network destination / Netmask	Mode	Next hop	Metric
1	192.169.1.002/32 (H3)	Land	192.168.1.003 (R1)	320, 0.32
2	192.169.4.0/24 (H4, H5)	Land	192.168.1.003 (R1)	520, 3.17
				670, 2.22
				720, 0.47
3	192.169.5.0/24 (H6, H7)	Land	192.168.1.003 (R1)	520, 3.17
				820, 0.52

Table 6. Routing table in R3

ID	Network destination / Netmask	Mode	Next hop	Metric
1	192.168.1.0/24 (H1, H2)	Land	192.169.1.001 (R4)	610, 0.41
2	192.168.1.0/24 (H1, H2)	Sea	192.168.2.001 (R2)	260, 2.06
3	192.169.1.002/32 (H3)	Land	192.169.1.001 (R4)	310, 0.11
4	192.169.4.0/24 (H4, H5)	Land	192.169.4.001 (R6)	410, 0.16
5	192.169.5.0/24 (H6, H7)	Land	192.169.5.001 (R7)	510, 0.21

During the practical shipment process, the status of logistics network keeps fluctuating because of the changes in traffic status, freight terminal status and transportation resources supplying. These fluctuations will lead to varying shipment cost and time between any two nodes in the CPI network. However, the altering shipment cost and time will be reflected in corresponding routing tables in real time. And the Pareto optimal shipment route will be quickly updated based on the varied cost and time through the CPI routing protocols. We assume the freight terminal R3 encounters congestion, and the shipment time between R2 and R3 increases from 2 days to 3 days. In this case, the Pareto optimal shipment routes departing from R1 are shown in **Fig. 8**. As seen in this figure, all routes passing through the router R3 are no longer Pareto optimal and only router R5 is selected as the transferring center if the sea transportation mode is used. When the shipment cost between the R1 and R4 rises from 300 to 600 dollars, the Pareto optimal routes departing from the R1 will be modified as shown in **Fig. 9**. We can find that the sea transportation mode is considered in

this case by transferring PSUs at R2 and R3, if the destination is R4. For shipping PSUs from R1 to R6, a new Pareto optimal route emerges in which the PSUs are directly shipped from R1 to R6 without any transferring (see the green route shown in **Fig. 9**). Nevertheless, the R4 is no longer selected as a transferring node for PSUs shipped from R1 to R7, instead, a direct land route to R7 is preferred.

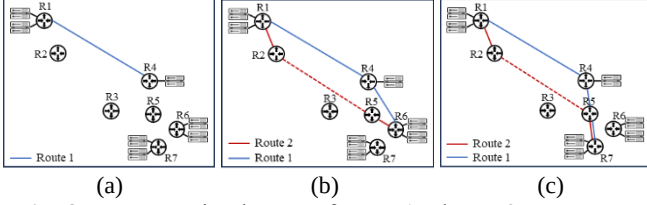


Fig. 8. Pareto optimal routes from R1 when R3 encounters congestion: (a) R1-R4; (b) R1-R6; (c) R1-R7

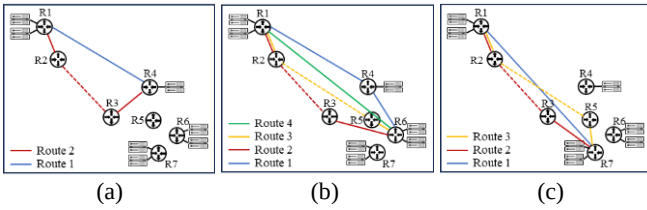


Fig. 9. Pareto optimal routes from R1 when shipment cost between R1 and R4 rises: (a) R1-R4; (b) R1-R6; (c) R1-R7

B. Performance in uncertain logistics environment

In this section, we consider some uncertainties of shipment time and cost among CPI nodes, which are expressed by a set of random variables obeying uniform distributions $U((1-\theta) \cdot X, (1+\theta) \cdot X)$. $\theta \in [0,1]$ is a coefficient influencing the variance of these random variables and X is the mean value of these random variables shown in the **Appendix B**. This setting means the shipment time and cost among CPI nodes are different for each PSU. The proposed routing protocol enables dynamic routing and transportation mode selection. Hence, the static routing decisions made in advance can be dynamically modified according to the varying cost and time. **Fig. 10** shows the shipment time and cost of transporting PSUs with different matrix preferences from R1 to R6, by adopting static and dynamic routing decisions. As seen in **Fig. 10**, dynamic and static decisions have similar performance when the variance is small ($\theta \leq 0.2$). But as the θ further increases, we can find that the dynamic decisions achieve both lower mean value and smaller range of fluctuation in terms of shipment cost and time. The reason is that the routing protocols can capture the varying shipment time and cost among routers and dynamically update the routing tables to adjust the route selections. This indicates that the proposed routing protocols can make route decision making more resilient in uncertain logistics environment.

C. Results in tractor type selection and PSU consolidation

Once the routing decisions are known for all PSUs at a CPI node, the scheduling decisions are subsequently made for them by determining the transportation resources and departure time. At this stage, the primary goal is to send all PSUs as punctually as possible. Because the shipment of some types of PSUs can

be only fulfilled by some specific tractors, the proportion of different tractor types will influence the scheduling results. **Fig. 12** depicts the average time difference for shipping PSU from R1 to R2, i.e., the objective function of PSU dispatching, when the tractor type proportion and decision period T are set into different values. As observed in **Fig. 12**, the average time difference fluctuates a little when the proportion of 3-axis tractor decreases from 0.4 to 0.3, which is about 0.1 days for $T = 3$ days. Nevertheless, as the proportion of 3-axis tractor further decreases from 0.3 to 0.2, a significant increase of the average time difference from 0.1 to 0.24 can be observed. The reason is that the PSUs in type 3 can be only shipped by 3-axis tractors, insufficient number of 3-axis tractors can lead to additional postponement time for PSUs in type 3.

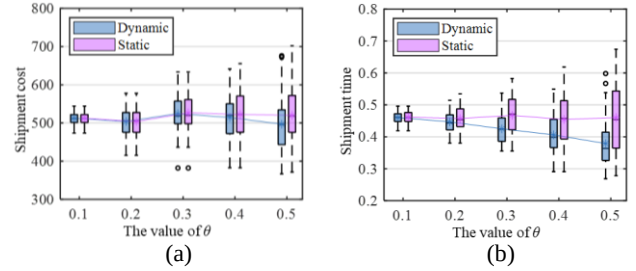


Fig. 10. Shipment cost and time comparison from R1 to R6 between dynamic and static routing methods: (a) PSUs with $\alpha_i = 0$; (b) PSUs with $\alpha_i = 1$

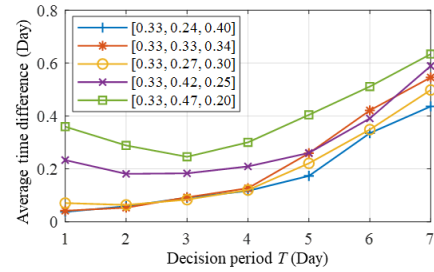


Fig. 11. Average time difference for different proportions of tractor types

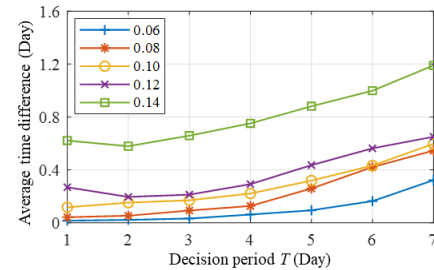


Fig. 12. Average time difference for different arrival rates of tractors

The length of decision period also imposes significant influence on the average time difference. Shorter T means we can utilize the revealed transportation resources more frequently but may also lead to some myopic decisions. As seen in **Fig. 11**, the decision period T should be set to 1 day if all types of transportation resources are sufficient for all types of PSUs. However, if the number of 3-axis tractors is insufficient (see the purple and green lines in **Fig. 11**), the decision period T should be increased to 2 days or 3 days to avoid myopic

tractor assignment. A similar conclusion can be made when we decrease the number of tractors. If the arrival rate is reduced to 0.12, i.e., about 8.3 fleets are revealed at router R1 every day, the optimal decision period will move from 1 day to 2 days. **Fig. 13** demonstrates the tractor assignment for different types of PSUs when the proportion of 3-axle tractors is 0.25. It is observed that many 3-axle tractors are used to fulfill 2-axle trailers if the decision period T is 1 day. These assignments are myopic because the 3-axle tractors remained could be insufficient for 3-axle trailers. As the decision period T increases to 7 days, fewer 3-axle tractors are assigned to 2-axle trailers, which can reduce the fulfillment time for 3-axle trailers.

PSU Type	Tractor Type			Tractor Type			Tractor Type		
	1	2	3	1	2	3	1	2	3
1	43	33	0	39	37	0	48	30	0
2	0	52	31	0	58	25	0	66	18
3	0	0	87	0	0	87	0	0	88
	$T=1$			$T=4$			$T=7$		

Fig. 13. Tractor assignment for different types of PSUs

6. CASE STUDY

In this section, we further introduce a case study base on a demonstration system developed in the laboratory to elaborate what makes operations different by applying the CPI and the five-layer model.

A. Layout design

This demonstration system simulates the construction and module logistics processes of a hospital in Hong Kong, where the modules are produced in mainland China. The layout is shown in **Fig. 14**, which is comprised of four parts, including construction site, prefabricated yard, industrial park and logistics.

Industrial park. There are two factories sharing one logistics hub in the industrial park. All modules should be moved to the logistics hub before furthering shipped to other places. We simulate the factory with a 3D printer to produce construction modules.

Prefabricated yard. There are three subareas in the yard, including inbound, outbound and storage areas, which are respectively responsible for module unloading, loading and storage.

Construction site. A hospital locates in the construction site, which is being built through module assembly. There is a buffer in the construction site, which has limited spaces to temporally store two modules at the most.

Logistics. The logistics involved in this system contain two parts, including local shipment and long-haul shipment. The local shipment includes short-distance (local) movements between factory-logistics hub, logistics-trucks, inbound area-storage area, buffer-building and so on. These movements are fulfilled by the two robots. For the long-haul shipment between

park-yard, park-site and yard-site, an automated guided vehicle (indexed as AGV001) acts as a truck to fulfill these tasks.

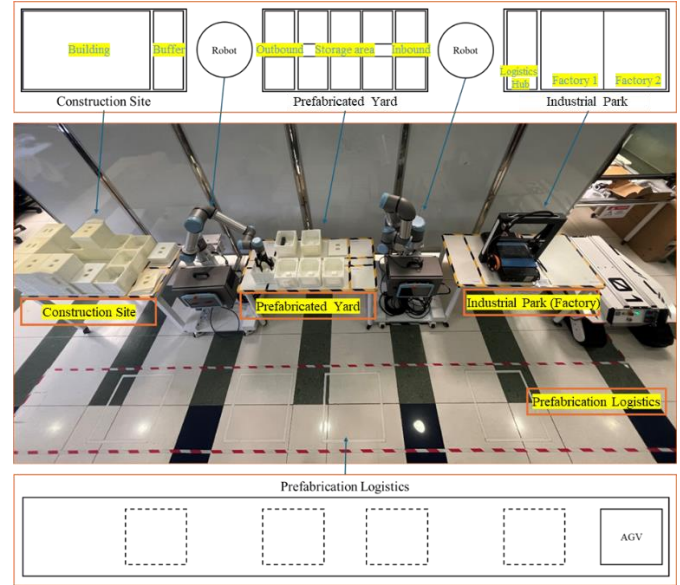


Fig. 14. The layout of the demonstration system

B. Digitalization technology

Real-time data is the ground to make shipment decisions with the CPI five-layer model. The CPI network involves a set of digitalization technology to collect data of shipment process. The most important one is the PSU status and decision data. The PSU status data, like location, are collected by an IOT sensor attached to the PSU (see **Fig. 15** (a)). The decision data, i.e., the information in PSU body, TCP, PIP, Link headers, are also stored in the IOT sensor.

The decision data is generated by the five-layer model, and the five-layer model is operated in CPI hosts/routers (see **Fig. 15** (b)) deployed at each logistics node. Physically, the CPI router is a microcomputer, which performs edge computing (run the five-layer model, update routing table), communicates with PSUs (read and write data of PSU) and communicates with other CPI routers (share routing table).

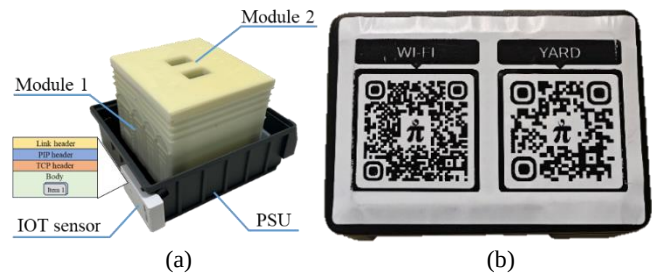


Fig. 15. CPI digitalization technology: (a) PSU; (b) CPI host/router

C. Operation process

The operation process of our demonstration system can be described in the following aspects:

CPI network configuration. This process initializes the whole CPI network by configuring CPI hosts/routes, assigning PIP addresses and indicating PSU types supported in the network. In the studied demonstration system, there are totally three

Ref. No.: T-ITS-24-07-2412

routers and four hosts are configured, and we manually allocate the PIP addresses for them, where the details are shown in **Table B.4 of Appendix B**. In addition to this, the system only supports one type of PSU (30*24*9cm box), which is shown in **Fig. 15 (a)**.

CPI capability table establishment. This process indicates what kinds of shipment resources can be used at each CPI host/router to create capability tables. **Fig. 16** presents an example of a capability table stored in the router of industrial park based on the direct connection status shown in **Table B.5 of Appendix B**.

PARK Cyber Physical Internet Router Decision Tables 						
Capability Table Save						
Id	Next hop	Mode	Cap(Unit)	Price(USD)	Time window	PSU type
1	192.168.0.001	Land	1	0	Any time	30*24*9cm box
2	192.168.0.002	Land	1	0	Any time	30*24*9cm box
3	192.168.1.002	Land	5	700	Any time	30*24*9cm box
4	192.168.2.002	Land	4	1000	Any time	30*24*9cm box

Fig. 16. CPI router capability table in industrial park

CPI routing table establishment. The capability table reveals the “physical connection” among CPI hosts/routers. With this information, the CPI routing tables can be updated according to the CPI routing protocols presented in Section 4.C. **Fig. 17** gives an example of the routing tables stored in the industrial park.

PARK Cyber Physical Internet Router Decision Tables 					
Routing Table					
ID	Network destination / Netmask	Mode	Next hop	Metric/ Unit(USD/ Min)	
1	192.168.0.001/32	Land	192.168.0.001	0, 0.05	
2	192.168.0.002/32	Land	192.168.0.002	0, 0.05	
3	192.168.1.0/24	Land	192.168.1.002	700, 0.4	
4	192.168.2.0/24	Land	192.168.2.002	1000, 0.6	

Fig. 17. CPI router routing table in industrial park

Shipment decision making. With the configured CPI network and necessary decision tables, the shipment decisions can be determined by the five-layer model at each CPI host/router in a hierarchical and decentralized manner. Specifically, taking shipping one Module 1 and Module 2 from Factory 1 to Building as an example, the decisions made at Factory 1 correspond to the five layers are listed as follows. 1. Application layer: create shipment orders with an app (see **Fig. 18**); 2. Transport layer: select empty 30*24*9cm box and shipped orders (ORD001) to create a PSU; 3. Network layer: given the generated PSU, determine its shipment mode (land), next hop (192.168.2.002), shipment resource (AGV) and departure time, which requires referring to the routing table and solving the PSU dispatching problem. 4. Link layer: resolve the MAC address and assign specific truck and driver (AGV001) to fulfill the shipment. When the functions of Transport, Network and Link layers are performed, the information will be written into the headers of the PSU by the host of Factory 1 (see

Fig. 19). Lastly, the Twin layer physically performs above all decisions, and both the digital and physical PSU will be received by the router in Site, where the PIP and Link header will be read and revised by running the Network and Link layers again. The process will be repeatedly made at each logistics node until the PSU is finally received by the receiving (destination) host.

Application Layer Dashboard							
Order list + Create Order Go to Transport Layer							
Order ID	Source	Destination	Items	Weight	Status	Delivery DDL	Action
ORD001	192.168.0.001	192.168.2.001	Module 1 (x1) - 0.8 kg each Module 2	1.1 kg	Pending	2025/5/15 09:00:00	  
ORD002	192.168.0.001	192.168.2.001	Module 1 (x1) - 0.8 kg each Module 2	1.1 kg	Pending	2025/5/20 13:00:00	  
ORD003	192.168.0.001	192.168.1.001	Module 1 (x1) - 0.8 kg each Module 2	1.1 kg	Pending	2025/5/22 09:00:00	  

Fig. 18. Software page of Application layer

Link header

From MAC: 04-EC-D8-44-4D-14 To MAC: BA-27-EB-3F-09-FB
Tractor: AGV001 Driver: AGV001

PIP header

Source PIP: 192.168.0.001 Destination PIP: 192.168.2.001
Next hop: 192.168.2.002 Remaining time: 3 mins
Shipment mode: Land Remaining cost: 1000 USD
Tractor type: AGV Departure time: 2025/05/22 08:59:00

TCP header

PSU ID: PSU183 Supported modes: Land, Sea
Delivery DDL: 2025/05/22 09:00:00 PSU type: 30*24*9cm box
Status: Not Loaded

Body (Orders)

 ORD001

[View Order](#)

Fig. 19. Information stored in the headers

D. What does CPI make current operations different?

Here we take the demonstration system as an example to explain what CPI makes current operations different. In current practice of module shipment, the decisions are generally made manually according to people’s experience. Meanwhile, all decisions, including route, mode, time and so on are static and made in advance. This leads to a gap to the optimal solution and slow response to cost and time uncertainty, especially in those large and complex logistics networks.

There are many powerful operational research methods that can be used to improve decision-making efficiency. Most of them involve developing a centralized optimization model, where the information of the whole logistics network is required to make an optimal decision. However, obtaining information at a system level is practically impossible considering the logistics networks are separated and operated by different

carriers. Different information systems used by various carriers make information integration quite challenging.

By introducing the PSU, CPI router/host and five-layer model, complex shipment decisions can be made in a hierarchical and decentralized manner. Each logistics node only determines a part of shipment decisions through the edge computing device (CPI host/router). Meanwhile, the CPI digitalization technology and TCP/PIP protocols achieve that necessary information is collected and shared among different logistics nodes in a standardized format, which avoid local optimality of shipment decisions.

7. CONCLUSION

In this study, we propose a suit of physical internet protocol for facilitating the module shipment in the prefabricated construction module logistics powered by the CPI. The development of PIP is inspired by the innovation of protocols in computer networks, which indicate what and how information should be shared or transmitted during the shipment process for making efficient decisions for the module shipments. With the support of physical internet and CPI routing protocols, a hierarchical shipment decision framework is developed to determine how the delivery resources are assigned to the construction modules and how these modules are transported in the CPI network. The module shipments in the CPI network can be fulfilled just like transmitting data packets in the computer networks, which demonstrates strong resilience against the uncertainties occur in the logistics networks. A set of experiments are conducted to verify the effectiveness of the proposed decisions framework based on real-life instances in the Greater Bay Area. The dynamic shipment strategy aided by CPI routers exhibits merits in handling uncertainties, which provides Pareto-optimal routing decisions in real time to guarantee the satisfaction of shipping time and cost requirements of construction modules. Meanwhile, a demonstration system is designed to elaborate how the CPI transform current shipment decision process of Modules.

There are several future research opportunities. For example, shipping construction modules do not involve crossdocking decisions. A crossdocking protocol to control the crossdocking spots for each PSU can be developed in the future, so that this protocol decision framework can be used in other logistics scenarios, like e-commerce order shipment. Meanwhile, the capacity of transferring centers is not considered in this study. Such a simplification may lead to overload of some transferring centers, so that future research should consider the limitation of transferring center capacity when selecting the next hops. Furthermore, this study only considers simple combinations between land and sea transportation mode. Future research can expand to synchro-modality among road, rail, inland waterways, shortsea, ocean freight, and air freight, and explore how the TCP/PIP model influences the performance of complex logistics networks.

ACKNOWLEDGEMENT

The authors would like to acknowledge partial financial supports from funding sources, including Hong Kong RGC TRS Project (T32-707/22-N), Collaborative Research Fund (C7076-22GF) and Research Impact Fund (R7036-22).

REFERENCES

- [1] S. Mahmoodi Khaniabadi, A. Javadpour, M. Gheisari, W. Zhang, Y. Liu, and A. K. Sangaiah, "An intelligent sustainable efficient transmission internet protocol to switch between User Datagram Protocol and Transmission Control Protocol in IoT computing," *Expert Syst.*, vol. 40, no. 5, Jun. 2023, doi: 10.1111/exsy.13129.
- [2] C. Yu and R. Y. Zhong, "An Internet Based 5-Layer Framework for Logistics in the Greater Bay Area," in *IEEE International Conference on Automation Science and Engineering*, IEEE Computer Society, 2023. doi: 10.1109/CASE56687.2023.10260392.
- [3] L. Luo *et al.*, "Supply Chain Management for Prefabricated Building Projects in Hong Kong," *Journal of Management in Engineering*, vol. 36, no. 2, Mar. 2020, doi: 10.1061/(asce)me.1943-5479.0000739.
- [4] A. Zaalouk, S. Moon, and S. Han, "Operations planning and scheduling in off-site construction supply chain management: Scope definition and future directions," *Autom Constr.*, vol. 153, p. 104952, Sep. 2023, doi: 10.1016/j.autcon.2023.104952.
- [5] Y. Jiang *et al.*, "Digital twin-enabled real-time synchronization for planning, scheduling, and execution in precast on-site assembly," *Autom Constr.*, vol. 141, p. 104397, Sep. 2022, doi: 10.1016/j.autcon.2022.104397.
- [6] Y. Zhao, P. A. Ioannou, and M. M. Dessouky, "Dynamic Multimodal Freight Routing Using a Co-Simulation Optimization Approach," *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 7, pp. 2657–2667, Jul. 2019, doi: 10.1109/TITS.2018.2871946.
- [7] P.-Y. Hsu, M. Aurisicchio, and P. Angeloudis, "Risk-averse supply chain for modular construction projects," *Autom Constr.*, vol. 106, p. 102898, Oct. 2019, doi: 10.1016/j.autcon.2019.102898.
- [8] George Q. Huang, "Cyber-Physical Internet (CPI) for Cross-Border Logistics of Manufactured Products,," Hong Kong, 2023. Accessed: Jul. 08, 2024. [Online]. Available: <https://innowings.engg.hku.hk/cyber-physical-internet/> accessed.
- [9] Z.-L. Wang, H.-C. Shen, and J. Zuo, "Risks in Prefabricated Buildings in China: Importance-Performance Analysis Approach," *Sustainability*, vol. 11, no. 12, p. 3450, Jun. 2019, doi: 10.3390/su11123450.
- [10] Y. Han, X. Yan, and P. Piroozfar, "An overall review of research on prefabricated construction supply chain management," *Engineering, Construction and Architectural Management*, 2022, doi: 10.1108/ECAM-07-2021-0668.
- [11] G. Xu, M. Li, L. Luo, C.-H. Chen, and G. Q. Huang, "Cloud-based fleet management for prefabrication transportation," *Enterp Inf Syst.*, vol. 13, no. 1, pp. 87–106, Jan. 2019, doi: 10.1080/17517575.2018.1455109.
- [12] Z. Wang, T. Wang, H. Hu, J. Gong, X. Ren, and Q. Xiao, "Blockchain-based framework for improving supply chain traceability and information sharing in precast construction," *Autom Constr.*, vol. 111, p. 103063, Mar. 2020, doi: 10.1016/j.autcon.2019.103063.
- [13] D. Lee and S. Lee, "Digital Twin for Supply Chain Coordination in Modular Construction," *Applied Sciences*, vol. 11, no. 13, p. 5909, Jun. 2021, doi: 10.3390/app11135909.

- [14] J. Y. Jang, S. Ahn, and T. W. Kim, "Cloud-based information system for automated precast concrete transportation planning," *Autom Constr*, vol. 152, p. 104942, Aug. 2023, doi: 10.1016/j.autcon.2023.104942.
- [15] B. Montreuil, "Toward a Physical Internet: meeting the global logistics sustainability grand challenge," *Logistics Research*, vol. 3, no. 2–3, pp. 71–87, May 2011, doi: 10.1007/s12159-011-0045-x.
- [16] B. Montreuil, R. D. Meller, and E. Ballot, "Physical Internet Foundations," 2013, pp. 151–166. doi: 10.1007/978-3-642-35852-4_10.
- [17] R. Sarraj, E. Ballot, S. Pan, and B. Montreuil, "Analogies between Internet network and logistics service networks: challenges involved in the interconnection," *J Intell Manuf*, vol. 25, no. 6, pp. 1207–1219, Dec. 2014, doi: 10.1007/s10845-012-0697-7.
- [18] R. Sarraj, E. Ballot, S. Pan, D. Hakimi, and B. Montreuil, "Interconnected logistic networks and protocols: simulation-based efficiency assessment," *Int J Prod Res*, vol. 52, no. 11, pp. 3185–3208, Jun. 2014, doi: 10.1080/00207543.2013.865853.
- [19] M. Plasch, S. Pfoser, M. Gerschberger, R. Gattringer, and O. Schauer, "Why Collaborate in a Physical Internet Network?—Motives and Success Factors," *Journal of Business Logistics*, vol. 42, no. 1, pp. 120–143, Mar. 2021, doi: 10.1111/jbl.12260.
- [20] Ray. Y. Zhong *et al.*, "Towards Physical Internet-enabled Prefabricated Housing Construction in Hong Kong," *IFAC-PapersOnLine*, vol. 48, no. 3, pp. 1079–1086, 2015, doi: 10.1016/j.ifacol.2015.06.227.
- [21] K. Chen, G. Xu, F. Xue, R. Y. Zhong, D. Liu, and W. Lu, "A Physical Internet-enabled Building Information Modelling System for prefabricated construction," *Int J Comput Integr Manuf*, vol. 31, no. 4–5, pp. 349–361, Apr. 2018, doi: 10.1080/0951192X.2017.1379095.
- [22] F. E. Achamrah, M. Lafkihi, and E. Ballot, "A dynamic and reactive routing protocol for the physical internet network," *Int J Prod Res*, vol. 62, no. 13, pp. 4735–4753, Jul. 2024, doi: 10.1080/00207543.2023.2274340.
- [23] S. Sun, C. Cassan, and C. Macharis, "Communication is computation: A privacy-protecting routing protocol for Physical Internet," *Transp Res E Logist Transp Rev*, vol. 191, p. 103710, Nov. 2024, doi: 10.1016/j.tre.2024.103710.
- [24] E. Ballot, B. Montreuil, and Z. G. Zacharia, "Physical Internet: First results and next challenges," *Journal of Business Logistics*, vol. 42, no. 1, pp. 101–107, 2021, doi: 10.1111/jbl.12268.
- [25] S. He, M. Zhang, S. Wang, and G. Q. Huang, "Pricing and revenue allocation mechanisms for regional logistics networks in Cyber-Physical Internet," *Transp Res Part C Emerg Technol*, vol. 165, p. 104714, Aug. 2024, doi: 10.1016/j.trc.2024.104714.
- [26] H. Wu *et al.*, "Towards cyber-physical internet: A systematic review, fundamental model and future perspectives," *Transp Res E Logist Transp Rev*, vol. 197, p. 104051, May 2025, doi: 10.1016/j.tre.2025.104051.
- [27] H. Wu, L. Huang, M. Li, and G. Q. Huang, "Cyber-Physical Internet (CPI)-enabled logistics infrastructure integration framework in the greater bay area," *Advanced Engineering Informatics*, vol. 60, p. 102551, Apr. 2024, doi: 10.1016/j.aei.2024.102551.
- [28] X. Qu, M. Li, Z. Ouyang, C. Ng, and G. Q. Huang, "Routing protocols for B2B e-commerce logistics in cyber-physical internet (CPI)," *Comput Ind Eng*, vol. 193, p. 110293, Jul. 2024, doi: 10.1016/j.cie.2024.110293.
- [29] C. Ng, M. Li, R. Y. Zhong, X. Qu, and G. Q. Huang, "Establishing carbon footprints for modular integrated construction logistics using cyber-physical internet routers," *Transp Res D Transp Environ*, vol. 133, p. 104259, Aug. 2024, doi: 10.1016/j.trd.2024.104259.
- [30] Z. Yuan, Z. Ouyang, Qi. Chen, M. Li, Z. Zhao, and G. Q. Huang, "Shipment Planning Protocols in Cyber-Physical Internet for Modular Integrated Construction Logistics," *SSRN*, 2024, doi: 10.2139/ssrn.4891853.
- [31] P.-Y. Hsu, P. Angeloudis, and M. Aurisicchio, "Optimal logistics planning for modular construction using two-stage stochastic programming," *Autom Constr*, vol. 94, pp. 47–61, Oct. 2018, doi: 10.1016/j.autcon.2018.05.029.
- [32] Y. Fang and S. T. Ng, "Genetic algorithm for determining the construction logistics of precast components," *Engineering, Construction and Architectural Management*, vol. 26, no. 10, pp. 2289–2306, Sep. 2019, doi: 10.1108/ECAM-09-2018-0386.
- [33] P.-Y. Hsu, M. Aurisicchio, and P. Angeloudis, "Optimal logistics planning for modular construction using multi-stage stochastic programming," *Transportation Research Procedia*, vol. 46, pp. 245–252, 2020, doi: 10.1016/j.trpro.2020.03.187.
- [34] A. Karam and K. H. Reinau, "A Real-Time Decision Support Approach for Managing Disruptions in Line-Haul Freight Transport Networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 12, pp. 24765–24777, Dec. 2022, doi: 10.1109/TITS.2022.3193956.
- [35] H. Wang, L. Liao, W. Yi, and L. Zhen, "Transportation scheduling for modules used in modular integrated construction," *Int J Prod Res*, pp. 1–14, Aug. 2023, doi: 10.1080/00207543.2023.2251602.
- [36] R. B. Larsen, W. Guo, and B. Atasoy, "A real-time synchromodal framework with co-planning for routing of containers and vehicles," *Transp Res Part C Emerg Technol*, vol. 157, p. 104412, Dec. 2023, doi: 10.1016/j.trc.2023.104412.
- [37] "Reference Material on Logistics and Transport for Modular Integrated Construction Projects," 2020.