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A carbon-aware routing protocol for optimizing carbon emissions in modular construction logistics*

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Abstract— **Amidst growing concerns over climate change and the pressing need for industries to reduce their carbon emissions, modular construction is a variable solution that applies in the construction industry. In the quest to manage the multiple actors and reduce carbon emissions in Modular Construction Logistics (MCL), our research proposes a Cyber-Physical Internet (CPI) network framework to introduce an integrated solution for multiple actors. Then, to optimize carbon emissions in MCL, we propose a carbon-aware routing protocol for making routing decisions in the proposed framework. The routing algorithm integrates a unique set of criteria, including module weight, travel distance, and carbon emission factors, in life cycle assessment to provide routing decisions with the lowest carbon emissions. The paper presents a detailed implementation of the algorithm, emphasizing its adaptability to the specific challenges of MCL, such as the optimization of transport routes to minimize environmental impact. Through numerical studies, we demonstrate the efficacy and feasibility of the proposed routing algorithm in reducing carbon emissions, thereby contributing significantly to the sustainability goals of the construction industry. Our findings not only highlight the potential for significant environmental benefits but also pave the way for further innovations in logistics management, aligning with global efforts towards carbon neutrality.**

I. INTRODUCTION

Modular construction emerges as a sustainable and viable approach within the construction industry, recognized for its capacity to mitigate environmental impact, enhance building efficiency, and reduce construction timelines [1]. This method has gained considerable attention globally due to its contributions toward reducing the environmental effect of the construction process and high efficiency. In addition, in the context of escalating climate change concerns, which have propelled sustainable development to the forefront of international agendas, numerous countries have implemented a range of initiatives and policies to require industries and the public to reduce and monitor carbon emissions for achieving carbon neutrality. Given that the construction and logistics sectors are two major contributors to carbon emissions, managing and reducing carbon emissions in module construction logistics is pivotal in steering these industries towards achieving carbon neutrality and sustainable development.

Ensuring an adequate supply of materials is essential for enhancing the success of modular construction. The availability of necessary resources plays a pivotal role in the efficiency and effectiveness of module construction, particularly in addressing housing challenges and emergencies and promoting sustainable development in densely populated cities. However, without a reliable supply of materials, the manufacturing process can be impeded, leading to delays in the construction sites. Furthermore, the significance of material supply becomes particularly evident in emergency scenarios, such as the rapid establishment of relief shelters or temporary hospitals during crises like the COVID-19 pandemic [2]. The ability to respond promptly and effectively relies heavily on the availability of readily accessible modules. Ensuring an uninterrupted flow of materials can significantly ensure the manufacturing process, resulting in alleviating construction site workloads and saving considerable time [3]. As cities experiment with different modalities, such as modular integrated construction in Hong Kong and prefabricated prefinished volumetric construction in Singapore [4], the availability of suitable materials becomes even more critical. By establishing robust logistics and resource management, projects can be completed in a timely manner, effectively addressing housing challenges, emergencies, and sustainable development goals.

In the whole life cycle assessment of module construction, there are multiple stages with different actors, including the product stage, construct stage, use stage, and end-of-life stage. More specifically, many stages include logistics, such as shipping materials from supplier to manufacturer and shipping modules from manufacturer to construction sites. The logistics in the construction stage have been investigated to establish a digitalized carbon footprint framework for carbon reduction [5]. In this paper, we focus on the product stage with multiple suppliers in different cities to provide materials to various manufacturers. Such materials can be reinforcement, sand, and

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so on. According to our investigations and field visits to modular construction companies, two problems have been summarized as follows:

The first problem is how to integrate different actors to achieve resource sharing in a limited area in modular construction logistics (MCL). There are multiple actors in MCL, involving clients, suppliers, transport agencies, and contractors, interconnected through information sharing within a project to enhance project efficiency. In more detail, there are multiple suppliers that provide materials and various manufacturers for producing modules, lacking integrated solutions for numerous actors in MCL.

The second problem is how to improve the logistics management with carbon reduction in MCL. Operations in modular construction are characterized by fragmentation, lacking a unified logistics network that could facilitate the sharing and tracking of information and resources. On the contrary, the current research focuses on cost and efficiency optimization, with a noticeable deficiency in emphasis on carbon emissions reduction.

To address these problems, two questions should be investigated as follows:

(1) How to establish an integrated solution for multiple actors in MCL with the concept of CPI.

(2) How to optimize carbon reduction in routing protocol using proposed integrated solutions in MCL.

With further exploration of these existing research gaps, this paper proposed a CPI network framework aimed at establishing an integrated solution and mitigating carbon emissions within MCL. The concept of CPI is inspired by the idea of the physical internet (PI). The PI was presented by Montreuil in 2011 [6], providing a direction for the transformation in the logistics industry and further introduced as an open global logistics system through protocols, interfaces, etc. [7]. Then, many scholars explored the potential of PI in the logistics industry and invested in other industries. For instance, PI has been implemented to manage resources in inland shipping [8]. CPI is to establish a new paradigm for sending and receiving modules, like sending and receiving messages on the Internet.

The rest of this paper is organized as follows. Section 2 introduces the overall CPI networks framework. Section 3 illustrates the operation mechanism in this framework. The numerical studies and results are discussed in Section 4 for illustrating proposed framework. Section 5 summarizes the innovation in this paper.

II. CPI NETWORK FRAMEWORK

The CPI network framework is designed (Figure 1) to introduce the elements and operations mechanism in MCL, establishing a layered architecture using the concept of CPI. In more detail, the CPI network framework is established based on PI characteristics, and a cyber layer has been proposed for achieving integration and information collaboration [9]. The main elements in the physical layer are similar to those in the physical internet: materials in a fully loaded transport unit refer to PI-container, the link is different shipping routes, and the nodes are the suppliers, borders, and manufacturers for shipping materials among them. In more detail, the CPI network for MCL is established by CPI routers. The router is a key element for connecting and sharing data information in the network [10]. Based on this, we introduced the establishment of CPI networks for MCL by putting routers in key nodes, including suppliers, borders, and manufacturers, to connect MCL. Besides, the CPI routing table is another key element in CPI networks to achieve carbon reduction in MCL. Each router has its own routing table for displaying the routing decision among various routes and indicating the next hop for shipping within routing protocols. Normally, the routing table includes destination, netmask, gateway, interface, and metric, and the metric often presents the shortest path in the network. In the CPI network, the metric can present the lowest cost, shortest time, shortest path, and lowest carbon emissions to provide different routing decisions under different conditions. In this study, the routing table is conducted regarding the specifics of a shipment in MCL, including the destination, the routing protocol, the next hop, the transportation mode, and the metric. More specifically, the routing table provides routing decisions for shipments following the routing algorithm and routing protocol.

A. The borders in the CPI network

In the cyber layer, we illustrate three area networks for integrating multiple suppliers and manufacturers for shipping materials. Firstly, we establish a CPI-local area network (CPI-LAN) for a single supplier or manufacturer, managing each company's internal logistics. In more detail, the local area network is a computer network that spans a limited geographical area, typically within a building, office, or campus. Secondly, we manage different suppliers or manufacturers in a CPI-catchment area network (CPI-CAN) to integrate similar enterprises in a city. CPI-CAN is similar to the concept of an industry cluster, which connects certain companies in various aspects of common service or behavior [11]. Furthermore, one of the existing papers introduced a border router placed at a customs or city border among various autonomous systems [12]. Thus, the CPI-CAN in this paper is composed of multiple firms with common businesses in a city. For example, several suppliers providing the same materials in a city are integrated into a CPI-CAN, and several manufacturers that produce similar modules in a city are integrated into a CPI-CAN. Thirdly, the CPI-wide area network (WAN) is used to connect different CPI-CANs in a large geographical area. A WAN is a computer network that extends over a large geographical area, connecting multiple LANs, individual devices, or CANs across different locations. Typically, WAN can encompass both LANs and CANs, providing connectivity across various locations and network types.

B. The operations mechanism in the CPI network

CPI Networks helps MCL provide an integrated solution for multiple actors with different responsibilities and cities, reducing the complexity of real-world shipment situations and achieving resource integration.

In the CPI-LAN, each enterprise has an independent CPI-LAN to manage internal logistics for themselves. As shown in Figure 1, for suppliers, the routers are set in the warehouse and the yard for loading and unloading for tracing the shipping information. When the suppliers receive orders from the manufacturers, the supplier starts to prepare the materials and ship them from the warehouse to the trucks. Analogously, the manufacturers place the routers at the yard and the factories receive the materials of a CPI-LAN. In the operation mechanism, each CPI-LAN focuses on its internal logistics, reducing the complex shipping situation and information in external shipment and improving the management of internal logistics.

In the CPI-CAN, there are multiple enterprises providing the common services or products in a city, such as several suppliers in a CPI-CAN and several manufacturers in another CPI-CAN. More specifically, the manufacturer places orders through the gateway from one CPI-CAN to another CPI-CAN; the routing decision is based on the demand and the traffic information between them. In a CPI-CAN, if the road is impassible or a traffic accident happens in a CPI-LAN, it will not be considered in this order.

The CPI-WAN helps CPI-CANs connect with each other to establish the CPI network framework in a large geographical area, such as the Greater Bay Area. More specifically, the border router updates information between each CPI-CAN for subsequent transport when the TUs are finished between them.

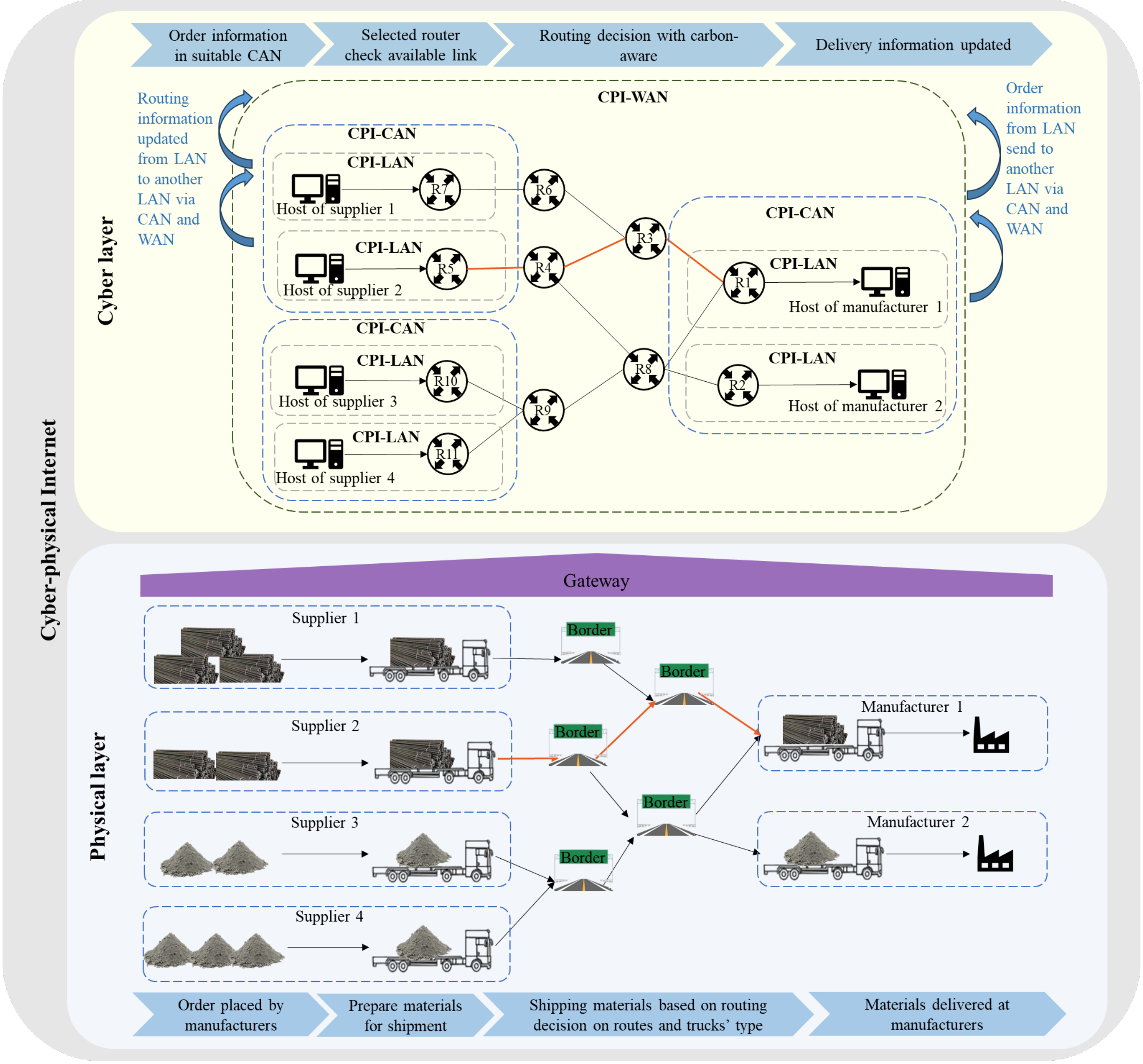

Figure 1. CPI Network Framwork

As shown in Figure 1, when the manufacturer in R1 orders materials from suppliers, R1 sends the order information and checks the available suppliers via CPI-CANs and CPI-WAN in the CPI network framework to other CPI-CANs for searching and placing orders. Thus, R1, via its CPI-CAN, connects to R3 first and then connects to R4 to connect to the suppliers' CPI-CAN via the CPI-WAN. Then, the order information is sent to supplier 2 for preparing materials via R5 in its CPI-LAN based on the routing metric, which is the lowest carbon emissions in this paper. After chatting and forming the currently available links in the CPI network, the router provides a routing decision based on the metric and provides the routing decisions in the routing table. This study considers the lowest carbon emissions for shipment to optimize carbon reduction based on real-world traffic information. Thus, the R5 is the most suitable supplier for shipping this order at the present moment. Then, the CPI-LAN is responsible for internal logistics to prepare and load units on trucks for shipment at R5. And then, the materials are shipped physically from supplier 2 to manufacturer 1 in Figure 1.

Algorithm 1 Routing algorithm

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Input: Graph $G = (V, E)$, start node $s \in V$, goal node $g \in V$, $Q_m$, EF
    for carbon emissions, blocked roads $B$, max car $M$, heuristic
    function $h$
Output: Find the minimum carbon emissions path using A* algorithm
Initialize distance map $D$ where $D[v]$ is the minimum known carbon
  emissions from $s$ to $v$;
Initialize heuristic map $H$ where $H[v]$ is the heuristic estimate of the
  carbon emissions from $v$ to $g$;
Initialize map $CarCount$ where $CarCount[v]$ tracks the number of cars
  used to reach $v$;
for each vertex $v$ in $V$ do
    Set $D[v] = \infty$;
    Set $CarCount[v] = 0$;
    Set $H[v] = h(v, g)$;
end
Set $D[s] = 0$;
Initialize a priority queue $Q$ and insert $s$ with priority $D[s] + H[s]$;
while $Q$ is not empty do
    $u$ = vertex in $Q$ with the smallest value of $D[u] + H[u]$;
    Remove $u$ from $Q$;
    if $u$ is $g$ then
        Construct the path from $s$ to $g$ by backtracking from $g$ to $s$ and
          return the path;
    end
    if $CarCount[u] < M$ then
        for each neighbor $v$ of $u$ with edge $e$ not in $B$ do
            $emissions = Q_m \cdot distance(u, v) \cdot EF$;
            $new\_cost = D[u] + emissions$;
            if $new\_cost < D[v]$ then
                $D[v] = new\_cost$;
                $CarCount[v] = CarCount[u] + 1$;
                Insert or update $v$ in $Q$ with priority $D[v] + H[v]$;
            end
        end
    end
end
```

III. ROUTING PROTOCOLS DESIGN FOR CARBON REDUCTION

To enhance the operations in the proposed framework, we introduce a carbon emissions routing protocol in this study. To integrate carbon emissions in the CPI networks, we integrate a carbon emissions algorithm from the life cycle assessment in the construction industry and the A* algorithm from the Internet. We changed the metric for making routing decisions to the lowest carbon emissions rather than the shortest path or bandwidth in the network. Based on this routing algorithm, the metric in the routing table displayed the carbon emissions for each road. More specifically, the first router shows the whole carbon emission for this shipment, and subsequent routers show the results from the current node to the final node. During the whole shipment, the router provides routing suggestions regarding current traffic information and link availability. If the link is impassible or the traffic is used for a longer time than other routes, the router will avoid this route and choose another lowest carbon emissions route in current situations. The companies can check the total carbon emissions for shipment through a routing table, which is more accessible than traditional operations by collecting data for calculation. Then, the routing algorithm in the proposed routing protocol is shown in the following:

IV. NUMERICAL STUDIES AND RESULTS

To verify and illustrate the routing protocol in the proposed integrated solutions in the CPI networks framework in MCL, we conduct a scenario analysis in the Greater Bay Area (GBA) for examination in this section. Two suppliers are at different locations in a city to provide materials, two suppliers at different locations in a city to deliver other kinds of materials, and two manufacturers at different locations in a city to produce similar modules. The assumptions for this scenario are as follows:

1. We use medium trucks and heavy trucks with different full-load capacities, including 8t, 10t, and 30t.
2. The location of each supplier and manufacturer is randomly set via simulation.
3. For each truck, we assume that it is fully loaded with different carbon emissions factors.
4. Each shipment is from one supplier to one manufacturer, so we don't consider consolidation in this section.
5. This scenario does not consider the fleet transport capacity and traffic real-time information.

A. Experimental results

In the simulation experiment of shipment from four suppliers to two manufacturers, the enterprises are formed into different CPI-LANs, CPI-CANs, and a CPI-WAN based on the border of area networks in the CPI networks. Thus, the two suppliers provide the same materials formed in one CPI-CAN, and the two manufacturers produced similar modules formed in one CPI-CAN, presenting a total of three CPI-CANs with six independent CPI-LANs in a CPI-WAN. Under the assumptions and specific constraints, we summarize a total of four scenarios with total shipping three times for suppliers, including shipping three times by 8t by one supplier, shipping three times by 10t trucks by one supplier, shipping three times by 30t trucks by one supplier, random shipping three times by different suppliers, and shipping three times by different suppliers under the integrated solution of CPI network. Since the nearest supplier cannot always meet the demand and cannot offer all the kinds of materials that the manufacturer needs, we can find that the integrated situation under the CPI network has the lowest carbon emissions for shipment, considering the real-world traffic information.

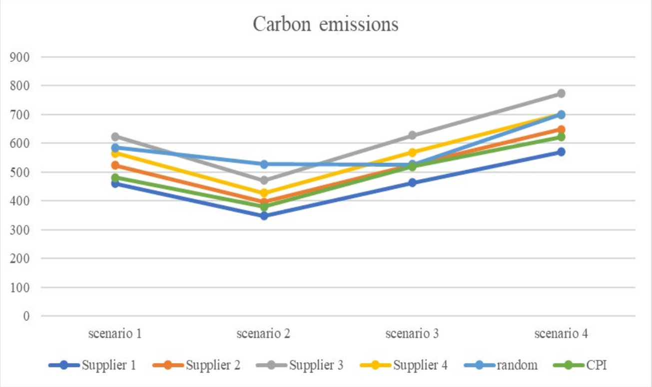

Figure 2. Carbon emissions of four lines

V. CONCLUSION

This paper introduces the development of a CPI network framework to advance an integrated solution for MCL, connecting multiple actors and reducing carbon emissions, contributing three major innovations to the field. The first innovation involves establishing an integrated solution utilizing the concepts of LAN, WAN, and CAN in the CPI network. The border of each area network for multiple actors in MCL is also set in this paper. The second innovation introduces a routing protocol in the proposed framework for carbon-aware routing decisions from each area network. This protocol is designed to assist the main stakeholders in MCL in reducing carbon emissions during the transportation phase. The third innovation pertains to managerial implementation. The proposed CPI network extends beyond the MCL industry, offering applicability to integrate multiple actors and help the logistics sector reduce carbon emissions. Additionally, it provides a foundation for governments and companies to make more informed routing decisions, thereby mitigating the occurrence of empty transports and unnecessary repetitive transportation.

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