Modular Containerization of Parcel Logistics Networks: Simulation-Based Impact Assessment

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Abstract: *The parcel industry has undergone significant changes in recent years, primarily driven by the surge of e-commerce and new technologies. The Physical Internet (PI) provides initiatives to optimize parcel flow and jointly address economic, operational, social, and environmental sustainability issues in the industry. Encapsulating parcels in modular PI containers is a promising method to enhance efficiency by consolidating parcel flows which can increase vehicle capacity utilization, leading to significant cost and transit time reductions. In this paper, we investigate the potential benefits of containerization in the parcel industry using simulation-based scenario designs and assessments. The results are evaluated across several performance facets, such as transport efficiency, handling operations, induced costs, and greenhouse gas emissions. The simulation results focusing on the East Coast region of the USA demonstrated that containerization and tiered mesh networks lead to cost savings and efficient space utilization, with multiple container sizes and a mesh network approach being more effective. This approach also reduces driving time per leg, improving efficiency and driver well-being. In conclusion, the study offers conclusive remarks and suggests further research avenues in this domain.*

Keywords: *Hyperconnected Logistics Infrastructure, Containerization, Modularization, Mesh Networks, Physical Internet, Routing Protocols, Network Architecture, Multi-tier Networks, Hyperconnected Service Network*

Conference Topic(s): *Modularization; PI fundamentals and constituents; PI impacts; PI implementation; PI modelling and simulation*

Physical Internet Roadmap: *☐ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☒ Access and Adoption, ☐ Governance.*

1 Introduction

In recent years, there has been a notable transformation in the postal and parcel industries, which can be attributed to the advent of e-commerce and pervasive technologies. This development has had a significant impact on logistics and freight transportation, resulting in an increase in business-to-consumer deliveries in certain areas and a rise in demand for swift and cost-effective deliveries. In response to these challenges, the Physical Internet framework has provided a range of avenues for optimizing parcel flow and address the economic, operational, social, and environmental sustainability concerns of the parcel industry supply chain.

In the literature on parcel logistics, economies of scale and flow consolidation have been identified as key techniques for cost reduction, improving service levels, minimizing transit time, enhancing sustainability, and ensuring timely delivery (Baumung et al., 2015). The parcel industry is characterized by a high volume of individual parcels that originate from various sources and are destined for multiple destinations, which favors PI-centric logistic network topologies for efficient consolidation and economies of scale (Gakis & Pardalos, 2017). However, one of the primary obstacles toward achieving efficient parcel flow is the sorting and handling of individual packages, which often have varying attributes such as volume, weight, shape, as well as conditioning and handling requirements.

Montreuil et al. (2018) proposed leveraging the concepts of hyperconnectivity and modularity to address the global challenges facing the parcel logistics industry, such as the need for faster and more sustainable delivery across urban areas, especially in megacities. The authors emphasized the need for disruptive transformations in package logistics hubs and networks, including multi-tier world pixelization through space clustering, multi-plane parcel logistics web, smart dynamic parcel routing, hub-based consolidation, and modular parcel containerization. In the study by Sarraj et al. (2014), the authors evaluate the efficiency of interconnected logistics networks and protocols through simulation-based assessments. They concluded that the integration of various logistics networks could lead to higher efficiency and sustainability, especially when combined with protocols that regulate the use of resources. Ballot et al. (2014), Meller et al. (2014), Montreuil et al. (2014), and Montreuil et al. (2021) propose functional designs for Physical Internet logistic hubs, each focused on a given application. Their studies highlight the importance of efficient and flexible transportation and handling processes to maximize the benefits of the Physical Internet. Venkatadri et al. (2016) address the impact of consolidation on transportation and inventory costs within the Physical Internet framework. Their results demonstrate that consolidation can lead to significant cost savings, especially for companies located far from their markets. Overall, these studies suggest that Physical Internet can bring about significant improvements in the efficiency and sustainability of logistics networks (Sallez et al., 2015), but careful design and implementation are essential for realizing its full potential.

The present study explores the feasibility of enhancing operations through the utilization of standard modular containers. These containers are envisioned to facilitate efficient handling and increase vehicle capacity utilization, which are fundamental components of the Physical Internet [Montreuil et al., 2011; Montreuil et al., 2016]. Specifically, we investigate the potential benefits of consolidating parcels into smartly designed containers that follow the same route. This approach aims to avoid the sorting process at congested hubs and achieve significant reductions in transit time and costs. Container consolidation involves combining individual parcel flows into larger-volume shipments that are destined for locations in the same general direction. This consolidation process is expected to streamline handling and sorting procedures, minimize the likelihood of packages getting damaged or misrouted during transportation, and result in time and effort savings. Notably, containerization can also relieve the sorting capacity burden at critical hubs as containers can be transshipped, bypassing the sorting process, and simplifying handling, loading, and unloading at the intermediary hubs.

Drawing upon our collaborative research with a major parcel logistics service provider, this research paper examines the potential of containerized ground network operations in the East Coast Region of the USA. To this end, simulation-based scenario designs and assessments were conducted, with the aim of analyzing the effectiveness of containerization in enhancing logistics network operations. The remainder of this article is structured as follows. Section 2 presents the conceptual model of the logistics network, specifying the scope and operations of the network. In Section 3, we describe the agent-based simulation model and dynamics, highlighting the various containerization scenarios that were developed. Section 4 presents the results of the simulations, comparing and discussing the findings from the different scenarios. Finally, in Section 5, we draw conclusions and propose avenues for future research and scalability. The study contributes to the ongoing discourse on the use of containerization in the parcel logistics industry and provides insights into its potential benefits and challenges.

2 Methodology

The parcel delivery process involves several key steps to ensure efficient and timely delivery. In this paper, we focus on in-network delivery operations, from first hub to the last hub, and exclude first and last mile operations. It begins with parcel origination, where parcels are collected, labeled, and sorted. Next, path assignment occurs, determining the route based on the origin, destination, and service level of the parcel (ODS) and network connections. A suitable truck is then assigned, considering capacity, availability, and estimated arrival time. Lastly, parcels may dwell in facilities for consolidation or sorting before continuing their journey to the destination.

In the current parcel delivery method, companies collect parcels and classify them according to size and service level requirements. At each facility, parcels can be consolidated into bags or moved as single units. Parcels are sorted and loaded into trailers for transport to the next facility. Trailers arriving from other facilities can be loaded or unloaded before onward shipment, or sent without being opened. Parcels and bags are scanned during the loading process to ensure proper handling and tracking.

The containerized parcel delivery method replaces all bags and trailers with modular containers. Parcels are loaded into at least one container when being transported and can be consolidated into larger containers as needed. This approach aims to improve efficiency, reduce handling time, and minimize potential damage to parcels during the transportation process.

By incorporating a mesh network with a fully containerized method, we can optimize parcel delivery by categorizing facilities into tiers and revising network edges and routing protocols. We classify facilities based on function, capacity, and location to ensure better resource management and workload distribution. We revise network edges to create a robust, adaptable and hyperconnected network that supports efficient routing. We update parcel and truck routing protocols using advanced algorithms and decision-making tools, which accommodate service level requirements, facility capacities, and network congestion.

The subsequent sections outline the methodology employed in parcel generation, network creation, and operational protocols to ensure efficient, timely, and transparent parcel delivery.

2.1 Demand Generation

To forecast parcel demand in the East Coast region of the USA, we obtain population data from each 5-digit zip code in the region, which serves as the basis for predicting parcel demand in each zip code. In addition, we enhance the accuracy of our parcel demand forecast by leveraging partner data on origin to destination flow proportions and trends. The data set encompasses 23 states, including New York, Pennsylvania, Florida, Georgia, Michigan, North Carolina, Ohio, Virginia, Tennessee, Indiana, South Carolina, Kentucky, Alabama, Maryland, Massachusetts, New Jersey, Mississippi, Connecticut, West Virginia, Delaware, Maine, Rhode Island, and Vermont. We use statistical distributions, specifically normal distributions based on the average weight and volume of packages shipped in the region, to assign weight, volume, and service level to each parcel. Finally, we generate a demand forecast for each zip code and assign weight, volume, and service level to each parcel accordingly.

Parcels are classified into small, regular, and irregular categories based on size and weight. Small parcels, like letters, can present handling challenges and are often transported in bags for efficiency. Regular parcels fit standard conveyor belts in sorting facilities, while irregular parcels have excessive volume, weight, or unusual shapes. Differentiating small parcels from regular ones is essential, as the aggregated size of small parcels impacts space and weight constraints within the logistics network.

Table 1: Parcel Types and their Weight-Volume Relationships

Parcel Type	*Weight(lb)*	*Volume (cubic inches)*
Small	< 10	< 450
Regular	≤ 75	< 10,000
Irregular	> 75	-

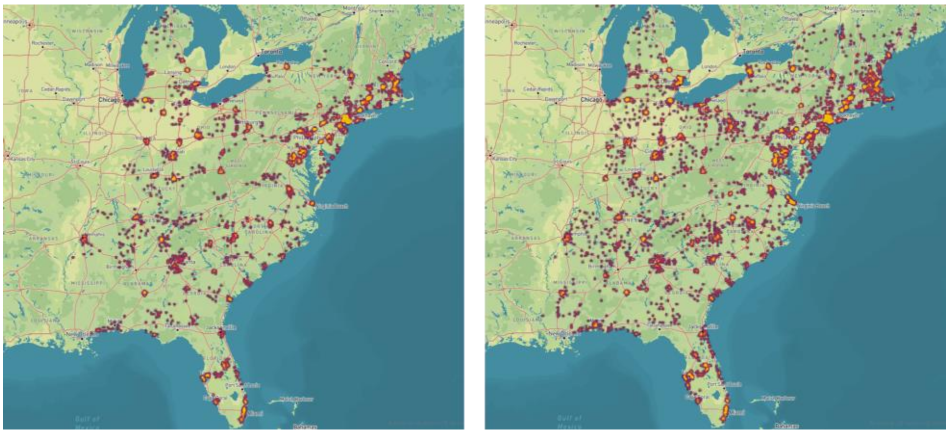

Figure 1: Geospatial heatmap representation of parcels generated over 10 days period (Left: Origins, Right: Destinations)

2.2 Hyperconnected Networks Creation

To create the hub networks for parcel logistics in East Coast USA to be contrasted through the simulation experiment, we analyzed demographic data to determine the population density of various regions and identify areas with high concentrations of potential customers. We also considered the location of major cities and major highway intersections, as they are typically associated with high levels of economic activity and generate significant parcel traffic. To further inform our decision-making, we analyzed historical flow and origin-destination pair trends from partner data to identify patterns in parcel delivery.

Based on our analysis, we identified potential hub locations, taking into account the surrounding regions that could be efficiently served by the hub. This allowed us to first create a base network of strategically placed hubs that could efficiently serve the surrounding regions while meeting the demands of customers for reliable parcel delivery services. The set of hubs in the base network includes all hubs displayed in the upper maps of Figure 2. The base network has allowed flow links between every pair of hubs, as it is based on direct point-to-point dispatch movement of freight, where a load is picked up at an origin and dropped at the destination.

Utilizing the same set of hub locations as the base network, we devised a system of hyperconnected tiered mesh networks for the physical internet. These networks comprise horizontal and vertical networks, each tier hosting its own horizontal network while vertical networks connect neighboring tiers. The tiered structure enables horizontal networks to function within a single tier, and vertical networks to link hubs in adjacent tiers. Mesh networks form within each tier, with direct links between nearby hubs. Hyperconnectivity is attained by incorporating 'hyperlinks' in vertical networks, interconnecting horizontal networks. Finally, networks are classified as open or dedicated, based on usage and accessibility.

The multi-tier, interconnected logistics network proposed by Montreuil et al. (2018) consists of six spatial cluster planes and corresponding hub resource tiers. Customer locations (plane 0) are clustered into unit zones (plane 1), which are then combined into local cells (plane 2), areas (plane 3), regions (plane 4), blocks (plane 5), and finally into our planetary world (plane 6). Corresponding hub tiers include access hubs (tier-1) networked in plane 1, local hubs (tier-2), gateway hubs (tier-3), inter-regional hubs (tier-4), global hubs (tier-5), and earth-planetary hubs (tier-6). These hubs are interconnected with nearby hubs within the same tier, as well as the tiers directly above and below.

Local hubs (tier-2) are situated within urban areas to facilitate parcel delivery within city limits, serving as secondary transfer points for parcels. Gateway hubs (tier-3), typically near major transportation hubs, serve as primary transfer points for parcels moving between areas, utilizing advanced sorting and tracking systems. Regional hubs (tier-4) handle the most consolidated load, equipped with infrastructure and technology to manage high parcel volumes. This multi-tier, multi-plane logistics network enables efficient and seamless parcel movement between various spatial clusters and hub resource tiers.

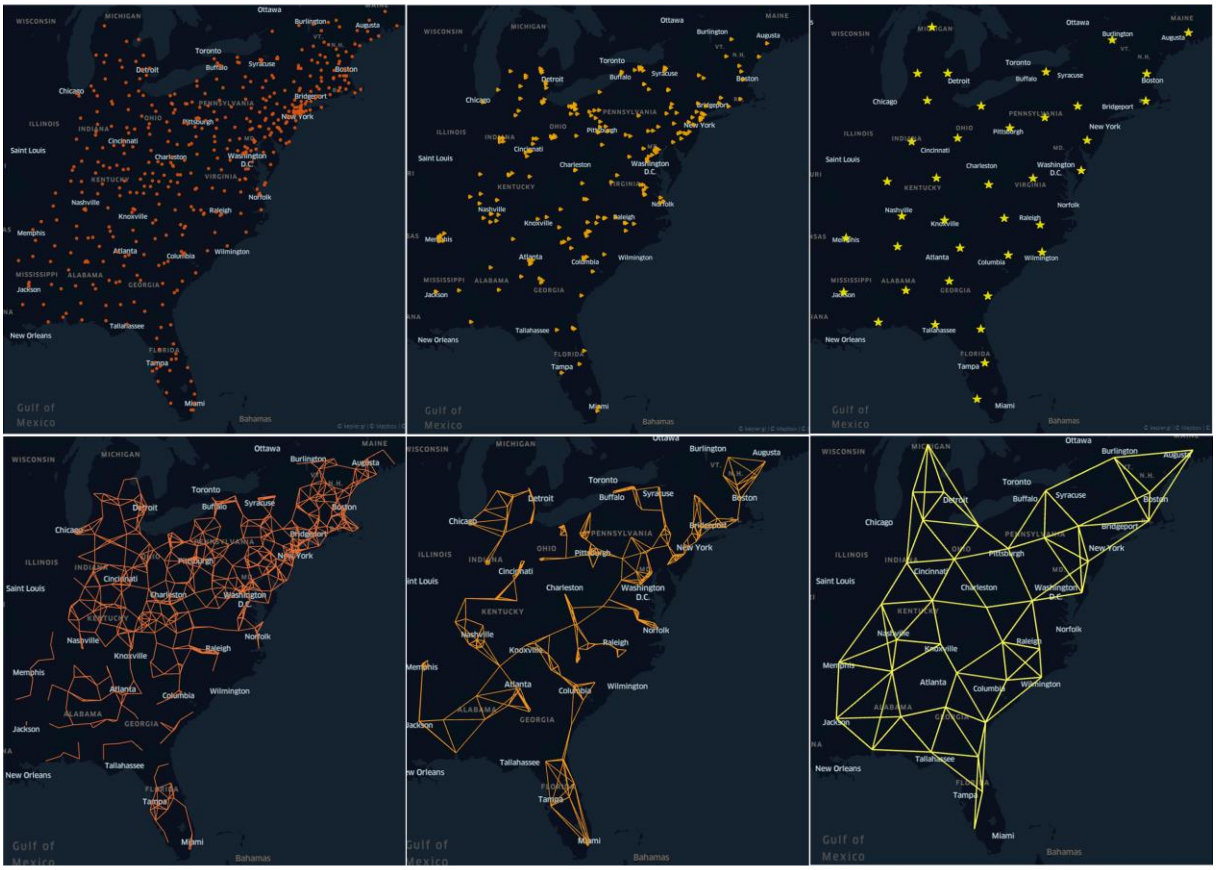

Figure 2: Showcasing the spatial distribution (top) and typical horizontal inter-hub flows (bottom) of local hubs (left), gateway hubs (center), and regional hubs (right)

2.3 Design Elements of Operational Protocols

This section examines key operational protocols in parcel management, including the parcel routing algorithm, bagging and containerization logic, and parcel sorting and trailer loading methodologies, all of which contribute to optimizing efficiency and ensuring timely, accurate deliveries.

2.3.1 Parcel Routing Strategies

When a package enters the system, three elements are already known: origin (O), destination (D), and service level (S). The parcel route determines the sequence of facilities that are visited by the parcel before it arrives at its destination. For the base network, we use the shortest path algorithm from origin to destination hubs to determine the parcel path while respecting the promised service level.

The base network parcel routing algorithm (Algorithm 1) identifies nearest hubs to origin and destination, calculates adjusted service level, generates feasible paths, and selects paths that maximize consolidation. Direct shipments are used when service level requirements cannot be met through planned routes.

Algorithm 1

procedure ParcelRoute(O, D, S) ▷ Origin, Destination, Service Level
    $H_O \leftarrow$ nearest hub to O, $H_D \leftarrow$ nearest hub to D, $S' \leftarrow (S -$ time to hubs$)$
    for each $O'D'S'$ combination **do**
        Generate k feasible paths considering S' constraints
        Select a path that maximizes consolidation
    end for
    if package cannot be delivered within S following the selected path **then**
        send parcel directly to D
    else
        send parcel via determined route, traversing hubs until it reaches H_D and finally D
    end if
end procedure

Algorithm 1: Parcel Routing in the Base Network

The parcel routing algorithm for mesh networks (Algorithm 2) effectively sends parcels between origins and destinations using a tiered hub system: local hubs (Tier 2), gateway hubs (Tier 3), and regional hubs (Tier 4). The algorithm checks for direct paths and identifies the nearest hubs of each type. It evaluates whether to escalate the parcel to a higher tier based on the optimal route. By strategically routing the parcel through the most suitable combination of hubs, the algorithm ensures efficient parcel delivery to the destination, while meeting the specific service requirements for each package (Shaikh et al., 2021).

Algorithm 2

procedure OptimalParcelRoute(O, D) ▷ Origin, Destination
    if direct path between O and D **then** ▷ Direct path
        send parcel directly to D
    end if
    $LH_O, LH_D \leftarrow$ nearest local hub to O and D ▷ Local Hubs
    if direct path between LH_O and D **then**
        send parcel via LH_O to D
    else if direct path between LH_O and LH_D **then**
        send parcel via LH_O, LH_D, and then to D
    end if
    $GH_O, GH_D \leftarrow$ nearest gateway hub to LH_O and LH_D ▷ Gateway Hubs
    if direct path between GH_O and LH_D **then**
        send parcel via LH_O, GH_O, LH_D, and then to D
    else if direct path between GH_O and GH_D **then**
        send parcel via LH_O, GH_O, GH_D, LH_D, and then to D
    end if
    $RH_O, RH_D \leftarrow$ nearest regional hub to GH_O and GH_D ▷ Regional Hubs
    if direct path between RH_O and GH_D **then**
        send parcel via LH_O, GH_O, RH_O, GH_D, LH_D, and then to D
    end if
    find shortest path from RH_O to RH_D using feasible regional hub connections
    send parcel via determined route, passing through regional hubs until it reaches RH_D, then send it to GH_D, LH_D, and finally to D
end procedure

Algorithm 2: Parcel Routing in the Hyperconnected Tiered Mesh Networks

2.3.2 Parcel Consolidation with Bags and Containers

Bags and containers use different consolidation rules due to their inherent handling requirement difference. Bagging consolidation is carried out in two stages. In the first stage, small packages with the same origin, destination, and service level are combined into a single bag at their point of origin. If this bag reaches at least a 50% fill rate, it remains sealed throughout its journey and is only opened upon arrival at its destination. However, if the bag's fill rate is below 50%, it undergoes further consolidation at the initial hub. Here, it is merged with other bags sharing the same first and last hubs, as well as the same hub service level. This newly consolidated bag is then opened at the final hub, where individual bags are created based on their respective destinations for the final leg of the journey.

In the mesh network, parcels enter the Tier-1 network and advance to higher tiers for long-distance transport. Upon arriving at a Tier-1 hub, a parcel's next destination is determined using the routing protocol. Consolidation within the mesh network employs π-containers in various sizes. In our case study, we opted for five modular container sizes: 1x1x2ft, 2x2x2ft, 2x2x4ft, 4x4x4ft, and 4x4x8ft. Container consolidation occurs on two levels. First, packages are elevated from the Tier-1 hub to the designated Tier-2 hub, if their paths involve higher tiers. At their Tier-2 origin (T2O), packages are consolidated into containers along with others sharing the same destination and service level (ODS). Some packages may not need to enter the Tier-3 hub network, depending on their service level and destination, and can travel within the Tier-2 network.

Packages with Tier-3 nodes in their paths are then elevated to assigned Tier-3 hubs, where they are further consolidated with other packages heading in the same direction. As each container incurs a handling cost upon de-consolidation at a hub, a fill rate threshold is assigned. If a container is at least 80% full, it remains sealed throughout the entire route and is only opened at the final Tier-3 destination. If a container is below the threshold at its initial hub, it is consolidated with other packages moving in the same direction and with the same service level at subsequent hubs. Once the containers reach their final Tier-3 destination, they are lowered to Tier-2 and then to Tier-1 for de-consolidation and ultimate delivery to the customer.

2.3.3 On-Demand Trucking

We leverage the on-demand trucking feature from the HyPTLI framework (Shaikh et al., 2021). On-demand trucks are utilized for transportation, with each vehicle being used for a single leg of the journey. These trucks share the same design and features, and it is assumed that they can accommodate up to three trailers each. Trucks are loaded with urgent parcels first, ensuring timely delivery as per the service promise. Once these high-priority parcels are loaded, other non-urgent parcels are added as fillers. This approach enables faster parcel movement through the system, optimizes truck and trailer utilization, and promotes effective consolidation.

3 Simulation Design

This section describes the structure of a discrete-event agent-based simulation developed in AnyLogic®. Figure 3 describes the simulation design, showing the interactions between active agents, passive agents, and objects in uncontainerized and containerized settings.

Active agents represent real-world entities and make decisions based on predefined rules or algorithms. In the simulation, six agents with specific roles collaborate for efficient parcel transportation and logistics, including the parcel router, loader/unloader, sorter/consolidator, bagging manager, containerizer, and equipment manager/router. Passive agents perform operations based on instructions without making decisions. Two passive agents, the demand generator and demand manager, collaborate in the system. They create and predict demand using statistical distributions or historical data.

Objects, non-autonomous entities, require agents' assistance for transportation. The simulation includes five object types: packages, vehicles, trailers, bags/containers and hubs. Each type possesses unique attributes and is managed by agents. The discrete-event agent-based simulation model enables the study and optimization of various system aspects, such as package scheduling and equipment utilization.

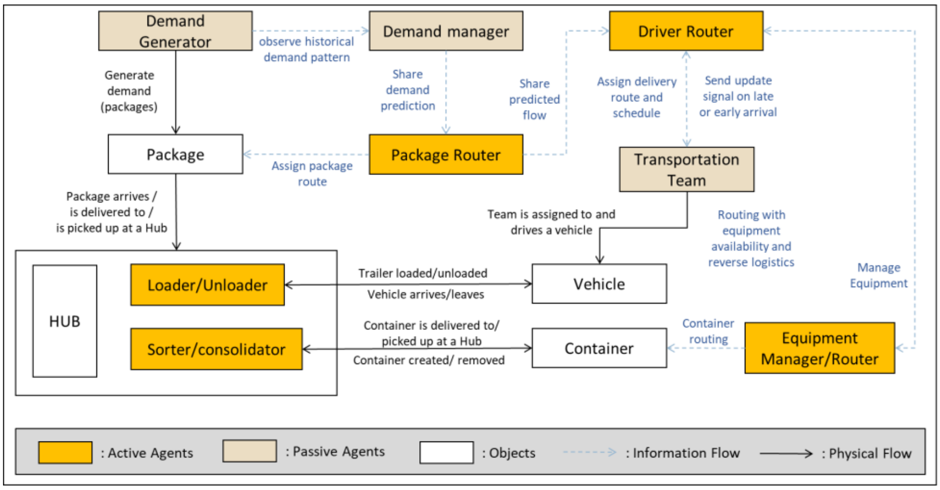

Figure 3: Simulation Model of Containerized Parcel Logistic Network

4. Experimentation

In our experimentation, we generated over 19 million parcels spanning ten days for the East Coast USA region. The base network consists of 713 hubs. As part of the transition to the mesh network, we implement a hub structure consisting of 457 local hubs, 217 gateway hubs, and 39 regional hubs organized into three tiers. To evaluate performance, we design and implement four different scenarios. The first scenario involves a base network without containerization, while the second scenario incorporates a single large container size (4x4x4) into the base network. In the third scenario, we utilize the base network with multiple container sizes, including small containers (1x1x2, 2x2x2, and 2x2x4) and large containers (4x4x4 and 4x4x8). Lastly, the fourth scenario involves a mesh network that utilizes multiple container sizes.

Table 2: Performance Evaluation Scenarios for Base and Mesh Networks with Containerization

Network/ Transportation	Containerization		
	No containers (NC)	Single Large Container (SLC)	Various Size Containers (VC)
Base Network	Scenario 1 (BN-NC)	Scenario 2 (BN-SLC)	Scenario 3 (BN-VC)
Tiered Mesh Network			Scenario 4 (MN-VC)

The cost structure used in the study was based on previous research conducted for an international parcel delivery company. Transportation costs were calculated as $2.5 per traveled mile. The handling costs were determined based on a cost-per-unit structure, with different costs for unloading, emptying, sorting, filling, crossdocking, and loading, depending on the parcel type. For example, the handling cost for an irregular parcel was $0.55 per unit, while the handling cost for a regular, small parcel was $0.15 per unit. Large containers had a higher handling cost of $1.61 per unit due to their size, while small containers had a lower handling cost of $0.27 per unit. These cost structures provided a standardized framework for the analysis of the cost savings associated with different parcel transportation strategies.

The cost table (Figure 4) indicates that scenario 2 (BN-SLC), which introduced a single large container size, resulted in an increase in total operations cost to $235 million compared to scenario 1 (BN-NC) without containerization. This suggests that the use of a single large container size led to an inefficient use of trailer space. Scenario 3 (BN-VC), which utilized multiple container sizes, resulted in a cost reduction to $161 million compared to scenario 2. This suggests that the use of a variety of container sizes allowed for a more efficient use of container and trailer space, contributing to the cost savings observed. Finally, scenario 4 (MN-VC), which implemented a mesh network with multiple container sizes, resulted in the most significant reduction in total operations cost to from $190M to $74M, resulting in savings of $116M. The savings are primarily from the reduction in sorting operations and loading/unloading operations. The component-wise handling cost is depicted in Figure 5.

	BN-NC	BN-SLC	BN-VC	MN-VC
Transportation Cost	$155 M	$217 M	$142 M	$60 M
Savings	-	($62 M)	$13 M	$95 M
% Savings	-	(40%)	9%	51%
Handling Cost	$35 M	$23 M	$12 M	$14 M
Savings	-	$12 M	$23 M	$21 M
% Savings	-	33%	65%	60%
Total Operations Cost	$190 M	$241 M	$154 M	$74 M
Savings	-	($51 M)	$36 M	$116 M
% Savings	-	(27%)	19%	61%

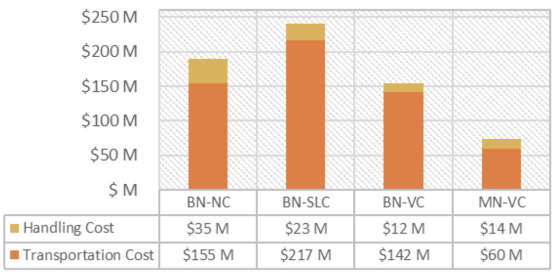

Figure 4: Cost comparison with Varying Degrees of Containerization and Mesh Network Implementation

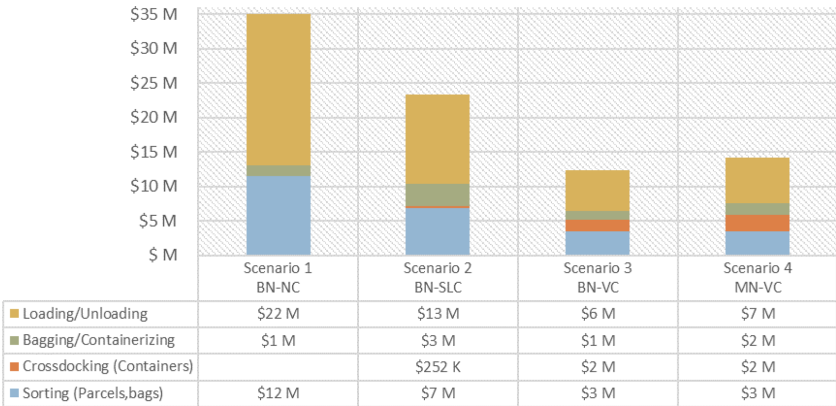

Figure 5: Component-wise handling cost for each scenario

The results show a significant reduction in transportation costs with the implementation of containerization and mesh network strategies. In scenario BN-NC, transportation costs amounted to $155 million, while in scenario MN-VC, transportation costs decreased to $60 million. This reduction is a direct result of reduction in the number of trips required to transport parcels. In scenario 4 (MN-VC), the total number of trips required was 174,618 which is on average 19% lower than the number of trips required in scenarios 1-3. This decline in the number of trips can be ascribed to the mesh network's more efficient use of container space. Additionally, there was almost a twenty-fold increase in the number of trucks that utilized three trailers in the mesh network compared to the base network. Furthermore, the environmental impact was also significantly reduced, with carbon emissions (CO_2 in kg) decreasing from 10.5 million kg to nearly 4 million kg, showing a reduction of 62%.

The study examined trailer fill rates in various scenarios, using two metrics: effective fill rate and trailer-container fill rate. The first metric, the effective fill rate, is calculated by dividing the parcel volume by the trailer volume. The second metric, the trailer-container fill rate, is determined by dividing the container volume by the trailer volume. Results showed that the effective fill rate was generally lower than the trailer-container fill rate, indicating underutilized container space. However, as scenarios progressed, more efficient space utilization was observed. Fill rate improvements were noted for all trailers.In scenario 1, average effective fill rate was 35% for trailer 1, while in scenario 4, the average effective fill rate for trailer 1 reached 57%. Similar improvements were noted for trailers 2 and 3. The trailer-container fill rate averaged at 58% in scenario BN-VC while at 80% in scenario MN-VC.

Two main transportation teams exist: regular feeder (single-driver) and sleeper (two-driver) teams. Sleeper teams are used for long-haul routes, but are more expensive and less desirable for drivers. As shown in Fig. 5, in the mesh network we are able to reduce average driving time per leg, that can almost eliminate sleeper team operations and enable return-to-home daily schedules for majority of drivers.

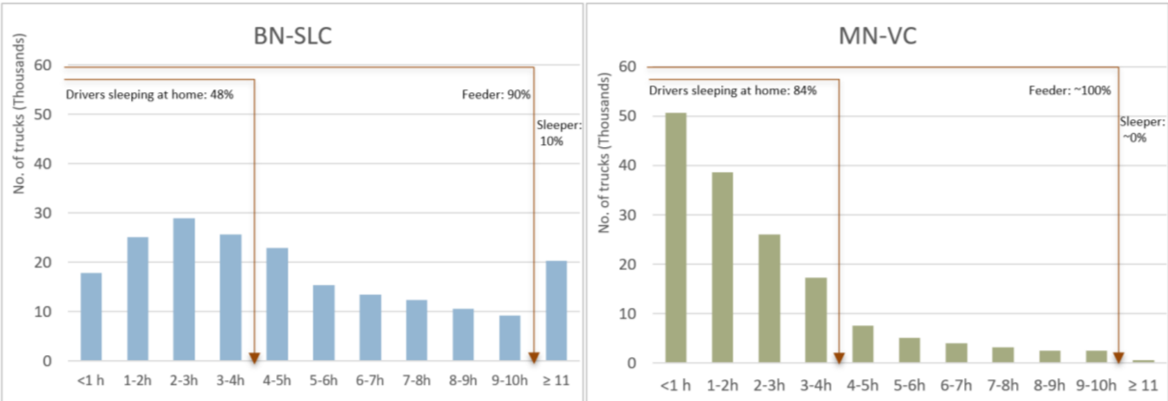

Figure 6: Comparison of Truck Leg Travel Time Distribution between BN-NC (left) and MN-VC (right) scenarios

4 Conclusion and Further Research

In conclusion, this study explores the effects of containerization and mesh network strategies on transportation costs, space utilization, and environmental impact. Findings reveal that using diverse container sizes and a mesh network approach significantly reduces operational expenses, improves space utilization, and fosters a greener transport system. The mesh network strategy also enhances driver well-being and overall efficiency. This research highlights the advantages of these strategies, emphasizing the importance of considering driver well-being and minimizing driving distances in transportation operations.

The current investigation into containerization and mesh network strategies in transportation operations reveals several promising directions for future research. One potential avenue is to examine the influence of other factors on transportation costs and efficiency, such as the nature of the cargo, the size and capacity of trucks, and the geographical location of transportation hubs. Investigating these factors will provide further insights into the efficacy of containerization and mesh network strategies. Additionally, future research could explore the application of advanced technologies, including automation and artificial intelligence, in transportation operations to optimize efficiency further. By delving into these future research directions, we can develop a more comprehensive understanding of transportation operations and provide practical solutions for enhancing efficiency, decreasing costs, promoting sustainability, and prioritizing driver well-being.

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