

Exploring the Effect of Network Configuration Topologies on the Dynamics of Freight Delivery: A Comparative Analysis of Physical Internet and Traditional Supply Chain Methods

Ruohao Chen and Uday Venkatadri

1. Dalhousie University, Halifax, Nova Scotia, Canada.
2. PI Networks, System of Logistic Networks, PI Nodes, Logistic hubs

Abstract

This paper compares the effect of network configuration on the dynamics of freight delivery. A comparison is made between Physical Internet (PI) and traditional distribution for the line, tree, square, circle, and cluster topologies. A mixed-integer linear program (MILP) model is presented to optimize the trade-off between dispatching and inventory costs. Quicker dispatch reduces inventory costs but increases the cost of transportation. This model is then applied for both the PI and traditional distribution contexts for each topology to understand the conditions favorable to PI. The key factors affecting the performance of the two methods are the distance ratio and the capacity of vehicles relative to dispatch flows. In terms of topology, the line configuration is always beneficial to PI but in the case of the other topologies, PI is good when the distance ratios and the flow quantity in relation to vehicle capacity increase.

1. Introduction

The literature on PI has grown considerably since 2010 when it was first introduced. In this paper, we are interested in the effect of the configuration and shape parameters of a logistics network to see how that impacts its operations within both the PI and traditional distribution constructs. The strength of PI lies in its ability to exploit the use of modular containers and create opportunities for consolidation.

Some standard PI configuration patterns are emerging in the literature. In Montreuil (2011), the point-to-point transportation physical internet case study had all the cities lined up (Figure 1.1). Fazili et al. (2017) consider a tree structure in Eastern Canada, which can be seen as a spine with offshoots (Figure 1.2). The case study in Li et al. (2022) can be clearly thought of as square grid (Figure 1.3). This can be thought of as a cluster like configuration with the hubs forming a network and a cluster of nodes in the vicinity of the hubs. Venkatadri et al. (2016) present a 26 city European PI network. A closer look at it reveals a hub and spoke structure which we call the circle configuration (Figure 1.4). Chadha et al. (2021) consider a case study in the automotive sector of Mexico (Figure 1.5).

The objective of this paper is to look at how well these PI network configurations compare when contrasted against their counterparts in point-to-point traditional networks. Specifically, we are interested in viewing the performance of a network based on the trade-off between dispatching and inventory costs. As evident, unless the arrival rate between two nodes in a point-to-point traditional network is very high, efficient dispatch implies waiting for loads, and therefore, shipments take longer. The PI network, on the other hand, offers opportunities for consolidation. Therefore, if there are opportunities for consolidation at a subsequent hub, a load might be opportunistically dispatched from a node to the closest hub to allow this to happen. Therefore, the hypothesis in this paper is that the dispatch rate and inventory cost trade-off take place differently. In this paper, we assume that all PI containers adhere to the tree-tier characterization of transport, handling, and packaging method proposed by Montreuil et al. (2010). This allows PI to generalize and standardize unit loads. The rest of this paper is organized as follows. Section 2 presents a brief literature on PI directly relevant to this paper. Section 3 presents two MILP models for dispatch planning: one for the traditional system and the other for PI. Section 4 shows how the experiments

to evaluate PI and traditional networks for the various configurations are designed. Section 5 presents some numerical results. Section 6 presents conclusions and Section 7 identifies some areas for future research.



Figure 1.1 (Adapted from Montreuil et al., 2011) Line shape case study conceptual transformation

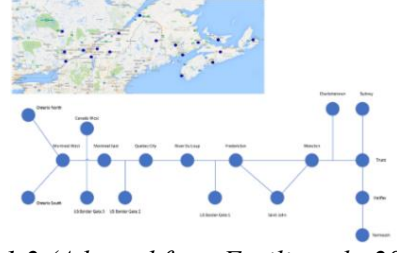


Figure 1.2 (Adapted from Fazili et al., 2017) Tree shape case study conceptual transformation

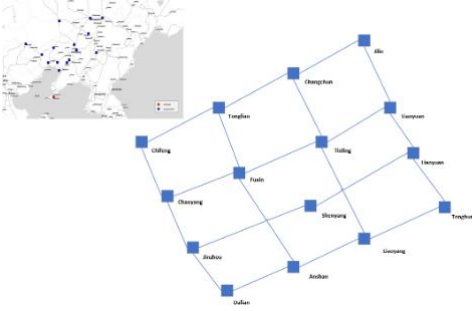


Figure 1.3 (Adapted from (Li et al., 2022) Square shape case study conceptual transformation



Figure 1.4 (Adapted from Venkatadri et al., (2016) Circle shape case study conceptual transformation

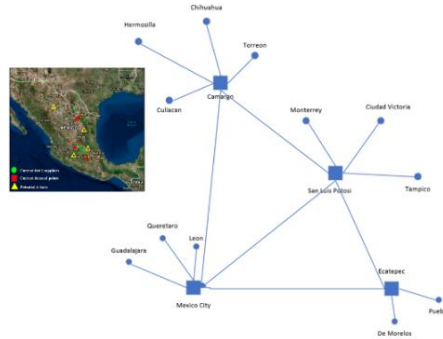


Figure 1.5 (Adapted from (Chadha et al., 2021) Cluster shape case study conceptual transformation

2. Literature Review

We present a brief history of the research relevant to dispatch planning in the PI starting with a foundational overview of essential physical elements underpinning the Physical Internet infrastructure, namely, containers, movers, and nodes (Montreuil, 2010; Montreuil et al. 2010). When simulating logistic network services using a model, employing unified units can streamline the complexity of the model. Transportation companies often use standardized units such as containers and vehicles. Montreuil et al. (2010) highlighted the importance of π -containers, which are unit loads manipulated, stored, and routed through the systems and the shared logistics infrastructure of the Physical Internet. These containers must adhere to standardized logistics modules worldwide and be designed to facilitate handling, storage, and transportation while ensuring the protection of goods. Ballot et al. (2010) developed a three-step topology evaluation of PI based on flow travel, transportation, and supply chain inventory. It is mentioned in the paper that the deployment of PI needs to show a significant reduction in the resources necessary to realize logistics operations through better operational efficacy, elimination of unnecessary journeys and use of more appropriate transportation means. A consequence of this transition toward the Physical

Internet can be the change of topology of the logistic service networks. Therefore, it is very important to study PI based on logistics configuration.

Ballot et al. (2012) describes the logistics paradigm for decentralized and distributed routing in PI compared to traditional centralized supply chain networks. Montreuil et al. (2012) explore the basis of the Physical Internet, designed to markedly improve the efficiency and sustainability of global physical object operations. Montreuil et al. (2012) proposed three types of PI business models: extension-driven business model, journey business models, and ephemeral business model.

Coming to transportation planning in PI, Hakimi et al. (2012) present a multi-agent mobility web simulator designed to facilitate the examination and analysis of the shift from the current freight transportation system to an open logistics network in France. Sarraj et al. (2013) presented a transportation protocol in PI and a container consolidation protocol, describing the basic logic of consolidation process in consolidation hubs. Lin et al. (2014) introduced a mathematical program and a decomposition algorithm to address the problem of optimizing space utilization when packing a collection of products. Ahmadi-Javid & Hoseinpour (2015) studied a profit-maximization location-inventory problem in a supply chain distribution network in uncapacitated and capacitated cases, determined location, allocation, price, and order size decisions to maximize the profit. Crainic & Montreuil (2016) present a synergy between City Logistic and Physical Internet, introduced the idea of Hyperconnected City Logistics system and its fundamental concepts, made a rich framework of designing efficient and sustainable urban logistics and transportation systems.

The current paper is based on the model in Venkatadri et al. (2016) who compare PI and the traditional logistics model based on dispatch optimization. The trade-off between delayed or expedited dispatch and inventory cost is considered for each pair of nodes in the two networks. Fazili et al. (2017) compare the performance of three logistics systems in a road network: conventional (CO), Physical Internet (PI), and a hybrid (HY) system. The study finds that the PI system reduces total driving distance but increases handling costs compared to CO and HY systems. Montreuil et al. (2017) presented a three-tier characterization of transport, handling and packaging containers for the Physical Internet to enable generalizing and standardizing unit load design worldwide. Chadha et al. (2021) explore how peddling, a traditional logistics consolidation strategy, can enhance a PI based automotive supply chain for three configurations: Model P (PI-based), Model S (standard peddling), and Model H (hybrid). They characterize the performance of the models for different types of cost, average distance traveled, and truck utilization. Ezaki et al. (2022) included three types of routing algorithms which are static shortest path (SSP) algorithms, temporary fastest path (TFP) algorithms, and adaptive fastest path (AFP) algorithm for PI. Li et al. (2022) suggested implementing the concept of PI by assigning a single request to multiple trucks, enabling transfers between trucks at logistics hubs, representing it as a PI-based selective vehicle routing problem (PI-SVRP).

Andersen et al. (2009) look at service network design with management and coordination of multiple fleets. Crainic & Hewitt (2020) present a comprehensive overview of the general service network design methodology, covering models, solution methods, and applications. Wang & Qi (2020) employ probability-free uncertainty sets to identify potential scenarios and develop a column-and-constraint generation approach as the solution method to solve the introduced robust models. All three papers have relevance to the issues studied in the paper, although space and scope limitations prevent us from exploring these issues. However, we focus instead on a gap in the PI literature which has to do with how the PI logistics system fares for the different configurations mentioned, namely the line, tree, square, circle, and cluster.

3. MILP Models for Dispatch

This section introduces two models employed in the designed logistic experiments: the

Traditional model and the PI model. The primary aim of these models is to plan dispatches in a network to optimize the total cost dispatch and waiting (inventory). Both the PI and Traditional models allow for two-way dispatches between nodes.

These models are extensions of the two-way model presented in Venkatadri et al. (2016), their logistic model minimize the total cost of inventory, transportation, fix costs, and variable costs, with constraints balancing the inventory level, dispatch and vehicle capacity, and the static initial and final states. For the PI model, there are some extra assumptions. Transshipment costs related to loading and unloading at source and destination points are not considered in the model because they do not change the decisions. However, these costs are added to the total cost of PI once a solution is found. In PI, the consolidation process is obligatory, requiring that all dispatch flows be routed through the consolidation hubs.

Following are the sets, parameters, and decision variables involved in both models:

Sets

N	The set of nodes
H	The set of hubs
NH	The set of nodes and hubs
V	The capacity of the vehicle (in same unit as arrivals)
C	Inventory cost per period per unit
F	Fixed cost for a truck cost
W	Variable vehicle (truck) cost

Parameters

A_{abt}	Number of orders that arrive at node a in period t destined for node b
d_{ab}	Distance from node a to b
w_{abc}	Binary, 1 if b is the next node when shipping from node a to c and b is not equal to c , 0 otherwise
z_{abc}	Binary, 1 if b is the next node when shipping from node a to c , 0 otherwise

Decision Variables

D_{abt}	Order quantity dispatched (in truck load) from node a to node b at the beginning of period t using truck type k .
N_{at}	Number of trucks at node a at the end of period t
I_{abt}	Order inventory (in truck load) at node a destined for node b at the end of period t
Y_{abt}	Number of trucks dispatched from node a to node b at the beginning of period t

3.1 Traditional Logistic Model (P2P)

In the traditional P2P model, all pairs of nodes are considered, and the flows occur both ways in each pair. However, the fleet of vehicles used to manage these flows are centralized.

minimize

$$\sum_a \sum_b \sum_t CI_{abt} + \sum_a \sum_b \sum_t (F + Wd_{ab})Y_{abt} \quad (1)$$

subject to:

$$I_{abt} = I_{a,b,t-1} + A_{abt} - D_{abt} \quad \forall a, b \in N, t = 1 \dots T \quad (2)$$

$$N_{at} = N_{a,t-1} + \sum_b Y_{bat} - \sum_b Y_{abt} \quad \forall a \in N, t = 1 \dots T \quad (3)$$

$$\sum_b D_{abt} \leq N_{at}V \quad \forall a, b \in N, t = 1 \dots T \quad (4)$$

$$D_{abt} \leq VY_{abt} \quad \forall a, b \in N, t = 1 \dots T \quad (5)$$

$$N_{a0} = N_{aT} \quad \forall a \in N \quad (6)$$

$$Y_{ab0} = 0 \quad \forall a, b \in N \quad (7)$$

$$I_{abT} = 0 \quad \forall a, b \in N \quad (8)$$

Objective function (1) seeks to minimize the total cost associated with handling and delivery. In Constraint (1), the first term accounts for the extra cost incurred due to consolidation, which results from delays in deliveries from source node 'a' to destination node 'b.' The second term encompasses the overall cost of vehicles, including fixed costs and transportation expenses, which are influenced by whether the vehicles are used or not. Constraint (2) addresses the balance of inventory, reflecting changes between consecutive periods. Constraint (3) concerns the equilibrium

of the number of vehicles used in two consecutive periods. Constraints (4) and (5) place limits on dispatch loads based on vehicle capacity and the total number of available vehicles, respectively. Constraint (6) ensures that the initial and final states remain consistent in terms of the number of vehicles. Finally, Constraints (7) and (8) represent the boundary conditions at the beginning, where no vehicles are in use, and there is no inventory at the source points, respectively.

3.2 PI Logistics Model

In this model, we introduce an additional set referred to as 'H,' representing consolidation hubs which are pertinent to PI. Corresponding adjustments have been applied to parameters with subscripts denoting points. Specifically, the inclusion of consolidation hubs has resulted in modifications to the following parameters and decision variables: A, d, D, N, I, and Y.

Two new parameters, namely w_{abc} and z_{abc} , have been integrated into this model. They serve as conditions mandating dispatch loads to pass through the consolidation hubs, thereby recreating the consolidation processes. Of these two variables, 'w' primarily functions to direct the flow along routes that initiate at source nodes, proceed to hubs for consolidation, and ultimately reach destination nodes (these are considered ideal routes). In constraint (10), 'w' is utilized to calculate inventory levels at transit points. Conversely, 'z' operates in a similar fashion to 'w,' but it allows flows to depart from consolidation hubs. This functionality enables the calculation of dispatch flows between every point, encompassing source nodes, consolidation hubs, and destination nodes, as specified in constraint (12).

Objective function (9) minimizes the total cost, the first term is the total inventory cost caused by consolidation. The second term of (9) is total fixed cost of vehicles, and the last term of (9) is total transportation cost of vehicles. In the second and third term of (9), the fixed cost and transportation cost are associated with the dispatch load of trucks from source node a to destination b and vice versa.

Constraint (10) is the inventory balance at each node or hub. Constraint (11) ensures that the total number of vehicles in the two consecutive periods are the same. Constraint (12) and (13) impose the limit on dispatch loads based on the number of vehicles and vehicle capacity. Constraint (14) ensures the initial state and final state are the same with total number of vehicles. Constraint (15) and (16) are the boundary conditions of the initial state (No vehicles being used and no inventory at any points, respectively). To conclude this section, the PI logistics model builds in the consolidation process into the optimization. However, it assumes a fixed routing which needs to be expanded in the future.

minimize

$$\sum_a \sum_b \sum_t CI_{abt} + \sum_a \sum_b \sum_t FY_{abt} + \sum_a \sum_b \sum_t Wd_{ab} Y_{abt} \quad (9)$$

subject to:

$$I_{bct} = I_{b,c,t-1} + A_{bct} + \sum_a D_{act} w_{abc} - D_{bct} \quad \forall b \in NH, c \in N, t = 1 \dots T \quad (10)$$

$$N_{at} = N_{a,t-1} + \sum_b Y_{bat} - \sum_b Y_{abt} \quad \forall a \in NH, t = 1 \dots T \quad (11)$$

$$\sum_c D_{act} \leq N_{at} V \quad \forall a, c \in N, t = 1 \dots T \quad (12)$$

$$\sum_a D_{act} z_{abc} \leq V Y_{abt} \quad \forall a, b \in NH, t = 1 \dots T \quad (13)$$

$$N_{a0} = N_{aT} \quad \forall a \in NH \quad (14)$$

$$Y_{ab0} = 0 \quad \forall a, b \in NH \quad (15)$$

$$I_{abT} = 0 \quad \forall a, b \in NH \quad (16)$$

4. Design of Experiments to Evaluate PI and Traditional Networks

The design experiments are categorized into two main sections: PI model logistic experiments and traditional model logistic experiments. The primary objective of these design experiments is to assess and compare the performances of PI and traditional logistics transportation methods under

various configurations and conditions. Six configurations are considered as shown below. The base distance unit between nodes (or hubs) is 300 km. The square configuration is of two types: the hubs only along the central line (Figure 4.3) and all nodes serving as hubs (Figure 4.4). All configurations have nine nodes.



Figure 4.1 Line configuration

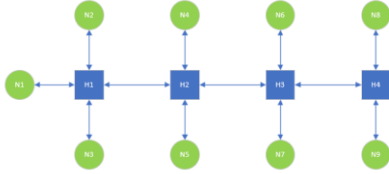


Figure 4.2 Tree configuration

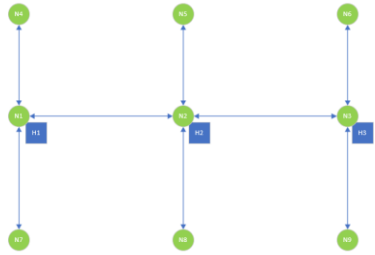


Figure 4.3 Central-line square configuration

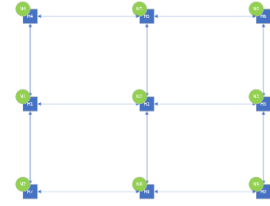


Figure 4.4 All-hubs square configuration

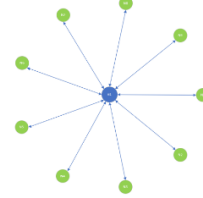


Figure 4.5 Circle configuration

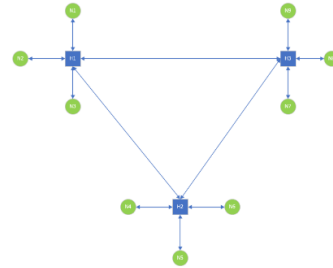


Figure 4.6 Cluster configuration (not to scale)

4.1. PI Distribution and Traditional Model Route Selection

In all PI model design experiments, the travel routes begin at nodes, proceed through one or more hubs, and ultimately reach the designated destination nodes. The distances between two points are composed of two components: node-to-hub (N-H) distances and hub-to-hub (H-H) distances. The cluster-type configuration in Figure 4.6 is not to scale because in the experiments we used all base distances to be 300 km, the hubs are strategically located at positions that have equal distances from all the nodes within each cluster, ensuring an even and balanced distribution.

4.2. Basic Experiment Parameters

For both the PI and Traditional logistic models, all design experiments consist of three periods, with loads from every node to all other nodes for each period. Consequently, each period comprises 72 dispatch flows, resulting in a total of 216 flows throughout the duration of each design experiment, maintaining consistency across both PI and traditional models. In the PI method, consolidation costs including loading, unloading and labor costs are added *priori* after the model is solved. When designing distance experiments, we commence with a standardized distance value of 300 kilometers for all distances. Subsequently, we systematically adjust the standard values of different types of distances, ranging from a quarter (0.25 times, equivalent to 75 kilometers) of the original value to eightfold (8 times, equivalent to 2400 kilometers) expansion in multiples. This meticulous approach generates a total of six distinct sets of results, each corresponding to a different scale of distance variations within the experiments. The size of dispatch loads is initially set to 4 between all node pairs. Subsequently, adjustments are made to the capacity of vehicles, starting from a minimum of 1 and increasing in multiples of two reaching

a maximum of 64. Consequently, this experiment produces a total of 7 sets of results, each corresponding to a different vehicle capacity setting. The base capacity of vehicles is initially 16. In experiments, we change it from 1 to 64 in multiples of two, yielding 7 distinct sets of results.

5. Numerical Results

5.1. Distance Experiment

Figure 5.1 illustrates the performance of adjusting H-H distances for all the shapes with H-H distances. From the plots of H-H distance experiments, all design experiments with shapes containing H-H distance have the same trend: when H-H distance increases, the growth rate of the cost curve of the PI method is slower than that of the traditional method. The performance of PI methods in most shapes will underperform the traditional method with small H-H distances at the beginning, outperforming it as H-H distance increases. One exception is the design experiment of the line shape, where PI is always superior. The reason for this is that in the line configuration, the distances are the same but there are opportunities for consolidation in PI. Figure 5.2 illustrates the performance of adjusting N-H distances for all shapes with N-H distances. From the grid of plots, the increase or decrease of N-H distance does not seem to produce a clear trend in performance change—there is no situation or trend where one method consistently outperforms the other with the increase or decrease. The all-hubs configuration has an advantage over the tree or central-line configurations for PI because for many node pairs, the flow does need to descend to the central-line. For this reason, the all-hubs configuration was not included in Figures 5.1 and 5.2. Figure 5.3 shows the effect of changing N-H or both N-H and H-H distances together. When the N-H increases, PI outperforms the traditional method. However, when both distances are increased together, there is no advantage for PI. Table 5.1 presents the total number of dispatched vehicles for each shape along with the average load per vehicle calculated under the condition of standard data in PI method. Through all three experimental periods, it is evident that all dispatch loads successfully reached their designated destination nodes by the end of the experiment, resulting in identical total transported loads for all configurations. The average load per vehicle reflects the degree of consolidation, with a higher number indicating a greater extent of consolidation. The line configuration exhibits the highest extent of consolidation, whereas the all-hubs square configuration demonstrates the lowest extent. The circle configuration uses relatively few vehicles and has a good degree of consolidation.

Table 5.1 Number of vehicles used during the experiment and average load per vehicle

<i>PI</i>	<i>Number of non-hub nodes</i>	<i>Number of hubs</i>	<i>Number of Vehicles</i>	<i>Total transported loads</i>	<i>Average loads per vehicle</i>
<i>Line</i>	2	7	90	864	9.6
<i>Tree</i>	9	4	170	864	5.1
<i>Square</i>	6	3	140	864	6.2
<i>Central-Line</i>					
<i>Square All-hubs</i>	0	9	177	864	4.9
<i>Circle</i>	9	1	108	864	8
<i>Cluster</i>	9	3	150	864	5.8

5.2. Experiment of Vehicle Capacity and Flow Quantity

The plots of vehicle capacity and flow quantity for all shapes are similar (Figure 5.4): as the vehicle capacity increases while keeping the flow quantities identical, the PI performance improves. For most shapes, except the line shape, the PI method will outperform the traditional method after reaching certain scales. In contrast, as the flow quantities increase while keeping the vehicle capacity identical, the traditional method starts to exhibit an advantageous performance

compared to the PI method because it can utilize capacity better. In fact, the ratio of flow quantity to vehicle capacity is the key factor (as shown in the bottom of Figure 5.4).

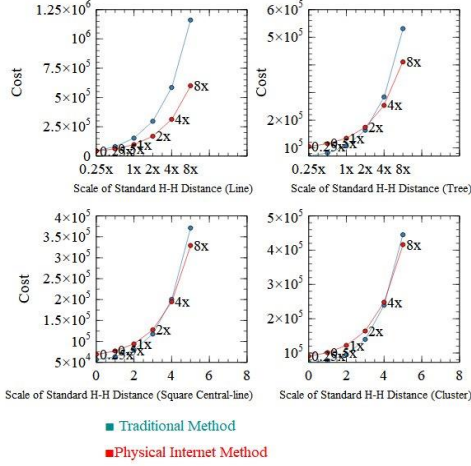


Figure 5.1 Plot of H-H distance experiments

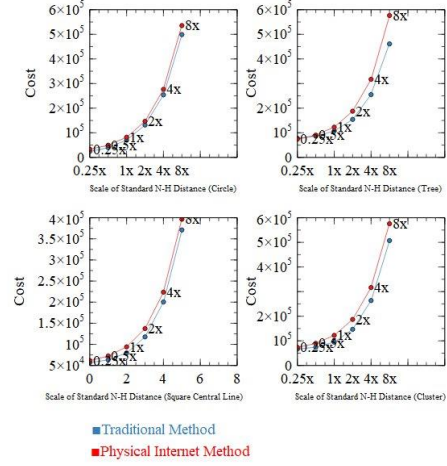


Figure 5.2 Plot of N-H distance experiments

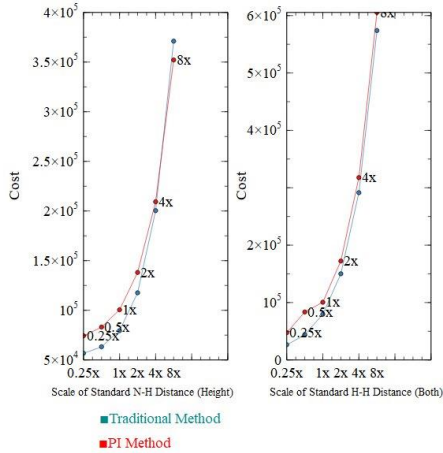


Figure 5.3 Plots of all-hubs square experiment

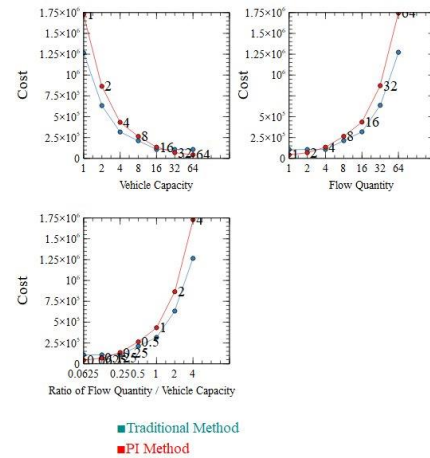


Figure 5.4 Plots of vehicle capacity and flow quantity experiments of tree experiment

6. Conclusion

The distance experiments show a trend for the various shapes. The smaller the ratio between the N-H and H-H distance, the more favorable it is for consolidation due to the clustering effect. On the other hand, increasing the N-H distance relative to the H-H distance makes the consolidated route distance much larger than the direct route distance in the traditional configuration, creating a condition that is not favourable to consolidation. In the experiments involving vehicle capacity and dispatch quantity, a smaller ratio of dispatch quantity to vehicle capacity results in each vehicle being able to transport more dispatch orders, leading to increased consolidation. As consolidation intensifies, the advantages of the Physical Internet (PI) model become more pronounced. Therefore, vehicle load capacity emerges as an important element in the success of the Physical Internet paradigm. From the design experiments conducted for each shape, it is evident that the Physical Internet (PI) method has its pros and cons in different scenarios. In the case of a line shape, except for extreme and unrealistic situations where transshipment costs at hubs are unusually high

compared to transportation costs, PI transportation consistently outperforms traditional methods. However, in tree, square, and circle shapes, there are specific dispatch orders where PI performs worse than traditional methods. In such cases, a hybrid approach combining traditional transportation and PI may be more suitable. In cluster-shaped scenarios, both N-H and H-H distance adjustments can lead to performance outcomes favoring either traditional or PI transportation.

Based on the travel distance of all utilized vehicles, the Physical Internet (PI) method demonstrates clear advantages over the traditional method. Consolidation results in the PI method covering about one-third of the transportation distance compared to the traditional method. This reduction is significant and greatly aids in reducing fuel consumption associated with transportation and will also save greenhouse gas emissions.

7. Future Research

This research can be extended in many ways. The experiments can be repeated for time windows, transshipment delay costs, and vehicle speeds such as in Li et al., 2022. This paper only looked at PI and traditional logistics systems. Hybrid systems where consolidation is not obligatory can be explored, as in Fazili et al. (2017). The effect of transshipment cost on network topology could be considered when comparing PI with the traditional system. The PI consolidation model in Section 3.2 assumes a fixed routing. While this is reasonable for the scope of this paper which was at an overall design evaluation level, it could be expanded to allow for dynamic routings at the operational level. The types of vehicles and containers can be varied to allow for mixed fleets.

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