

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

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Abstract

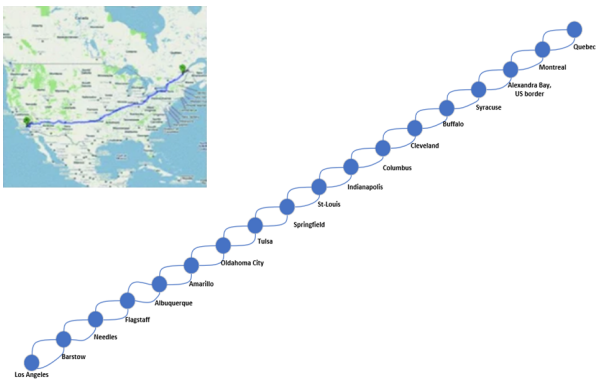
- ❑ We are interested in the effect of network configuration on the dynamics of freight delivery.
- ❑ Comparison between Physical Internet (PI) and traditional distribution for the line, tree, square, circle, and cluster topologies.
- ❑ A mixed-integer linear program (MILP) model is presented to optimize the trade-off between dispatching and inventory costs.
- ❑ We present our results through numerical experiments.

Introduction

- ❑ Can we view the performance of a network based on the trade-off between dispatching and inventory costs?
- ❑ Waiting leads to better dispatch efficiency but delay (represented by inventory cost).
- ❑ The PI offers good consolidation opportunities.
- ❑ Under what conditions can it reduce delay and yet be efficient in terms of dispatch?

Line Configuration

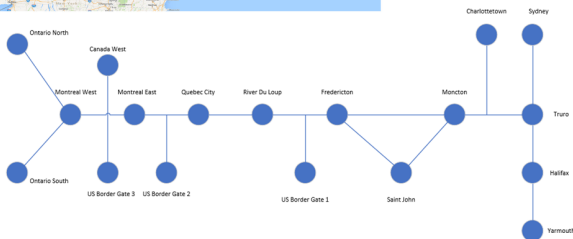
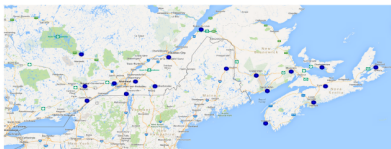
- ❑ Standard PI configuration patterns are emerging in the literature.
- ❑ In Montreuil (2011), the physical internet example had all the cities lined up.



Line Configuration

Tree Configuration

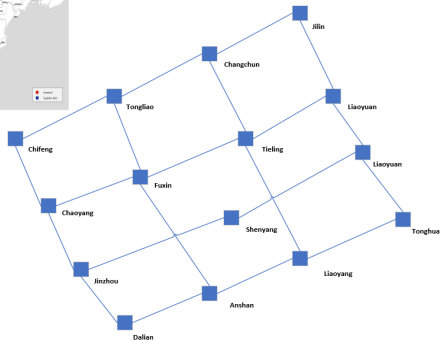
- Fazili et al. (2017) consider an almost tree-like structure in Eastern Canada, which can be seen as a spine with offshoots.



Tree Configuration

Square Configuration

- The case study of Li et al. (2022) can be clearly thought of as a square grid.



Square Configuration

Circle Configuration

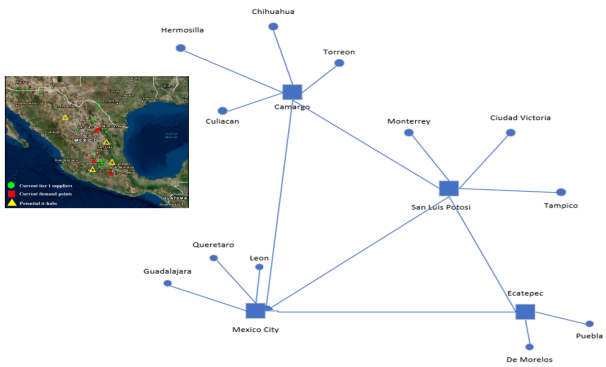
- Venkatadri et al. (2016) present a 26 city European PI network.
- It reveals a hub and spoke structure which we call the circle configuration.



Circle Configuration

Cluster Configuration

- ❑ Chadha et al. (2021) consider a case study in the automotive sector of Mexico.
- ❑ This is a cluster-like configuration with the hubs forming a network and a cluster of nodes in the vicinity of the hubs.



Cluster Configuration

Sets, Parameters, and Variables

Sets

N	Set of nodes
H	Set of hubs
V	Capacity of the vehicle
C	Inventory cost per period per unit
F	Fixed cost of a truck
W	Variable truck cost
T	Set of time periods

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

Variables

D_{abt}	Order quantity dispatched (truck loads) from node a to node b at the beginning of period t
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

Table: Sets, parameters, and decision variables involved in PI dispatch optimization model

Traditional Method

$$\text{Minimize: } \sum_{a \in N} \sum_{b \in N} \sum_{t \in T} C I_{abt} + \sum_{a \in N} \sum_{b \in N} \sum_{t \in T} (F + W d_{ab}) Y_{abt} \tag{1}$$

$$I_{abt} = I_{a,b,t-1} + A_{abt} - D_{abt} \qquad \qquad \qquad \forall a, b \in N, t \in T \tag{2}$$

$$N_{at} = N_{a,t-1} + \sum_{b \in N} Y_{bat} - \sum_{b \in N} Y_{abt} \qquad \qquad \qquad \forall a \in N, t \in T \tag{3}$$

$$\sum_{b \in N} D_{abt} \leq N_{at} V \qquad \qquad \qquad \forall a, b \in N, t \in T \tag{4}$$

$$D_{abt} \leq V Y_{abt} \qquad \qquad \qquad \forall a, b \in N, \forall t \in T \tag{5}$$

$$N_{a0} = N_a T \qquad \qquad \qquad \forall a \in N \tag{6}$$

$$Y_{ab0} = 0 \qquad \qquad \qquad \forall a, b \in N \tag{7}$$

$$I_{abT} = 0 \qquad \qquad \qquad \forall a, b \in N \tag{8}$$

PI Method

$$\text{Minimize: } \sum_{a \in NH} \sum_{b \in N} \sum_{t \in T} Cl_{abt} + \sum_{a \in N} \sum_{b \in NH} \sum_{t \in T} F Y_{abt} + \sum_{a \in N} \sum_{b \in NH} \sum_{t \in T} W d_{ab} Y_{abt} \quad (9)$$

Subject to:

$$I_{bct} = I_{b,c,t-1} + A_{bct} + \sum_{a \in NH} D_{act} W_{abc} - D_{abt} \qquad \forall b \in NH, c \in N, t \in T \quad (10)$$

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

$$\sum_{c \in NH} D_{act} \leq N_{at} V \qquad \forall a, c \in N, t \in T \quad (12)$$

$$\sum_{c \in N} D_{act} z_{abc} \leq V Y_{abt} \qquad \forall a, b \in NH, \forall t \in T \quad (13)$$

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

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

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

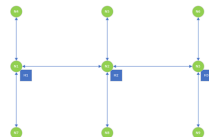
Configurations Considered



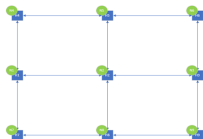
Line Configuration



Tree Configuration



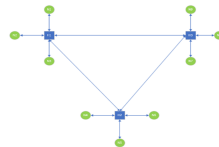
Central-line Square Configuration



All-hubs Square Configuration



Circle Configuration



Cluster Configuration

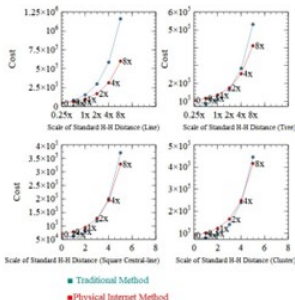
Vehicle Usage

- ❑ Average loads per vehicle reflects the degree of consolidation
- ❑ The line configuration has the most consolidation.
- ❑ The all-hubs square configuration demonstrates the lowest extent.
- ❑ The circle configuration uses relatively few vehicles and has good consolidation.

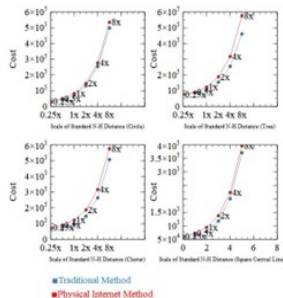
PI Config- uration	Num. non-hub nodes	Num. hub nodes	Num. vehicles	Total loads	Avg. loads/vehicle
Line	2	7	90	864	9.6
Tree	9	4	170	864	5.1
Sq. 1	6	3	140	864	6.2
Sq. 2	0	9	177	864	4.9
Circle	9	1	108	864	8
Cluster	9	3	150	864	5.8

Distance Experiment

- 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 increase or decrease of N-H distance does not produce a clear trend in performance change



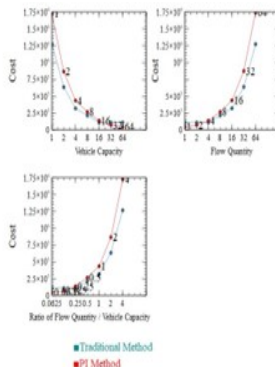
H-H Distance Experiment Result



N-H Distance Experiment Result

Vehicle Capacity and Flow Quantity Experiment

- ❑ As the vehicle capacity increases while keeping the flow quantities identical, the PI performance improves.
- ❑ For all shape except the line configuration, the PI method will outperform the traditional method after reaching certain scales.
- ❑ Conversely, 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.



Vehicle Capacity and Flow: Tree Configuration

Conclusion

- ❑ The network topology is a key factor governing performance.
- ❑ The smaller the ratio between N-H distance and H-H distance, the more favorable it is for consolidation.
- ❑ Vehicle load capacity emerges as an important element in the success of the Physical Internet paradigm.
- ❑ The Physical Internet (PI) method has its pros and cons in different scenarios.
- ❑ In the case of a line shape, except for extremely 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 order sizes 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.

Future Research

- ❑ The following factors can be added to the MILP models:
 - ❑ Time windows, transshipment delay costs, and vehicle speeds.
 - ❑ Hybrid systems that combine PI method and traditional method can be explored.
 - ❑ The effect of transshipment cost and network topology could be considered in tandem when comparing PI with the traditional system.
 - ❑ The assumption of fixed routes can be expanded to allow for dynamic routings at the operational level.
 - ❑ Multiple vehicle types could be considered.
 - ❑ Modular container sizes could be considered.

Partial Reference List

- ❑ B. Montreuil (2011). Toward a physical internet: Meeting the Global Logistics Sustainability Grand Challenge. *Logistics Research*, 3(2–3), 71–87.
- ❑ M. Fazili, U. Venkatadri, P. Cyrus, & M. Tajbakhsh (2017). Physical internet, conventional and hybrid logistic systems: A routing optimisation-based comparison using the Eastern Canada Road Network Case Study. *International Journal of Production Research*, 55(9), 2703–2730.
- ❑ M. Li, S. Shao, Y. Li, H. Zhang, N. Zhang & Y. He (2022). A physical internet (PI) based inland container transportation problem with selective non-containerized shipping requests. *International Journal of Production Economics*, 245, 108403.
- ❑ U. Venkatadri, K. S. Krishna & M. A. Ulku (2016). On Physical Internet Logistics: Modeling the impact of consolidation on transportation and inventory costs. *IEEE Transactions on Automation Science and Engineering*, 13(4), 1517–1527.
- ❑ S. S. Chadha, M. A. Ülkü, & U. Venkatadri (2021). Freight delivery in a physical internet supply chain: An applied optimisation model with peddling and shipment consolidation. *International Journal of Production Research*, 60(16), 4995–5011.

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Thank you!