On Comparing Dedicated and Hyperconnected Distribution Systems: An Optimization-Based Approach

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Abstract. The current distribution systems are mainly dedicated to a single business that owns or contracts a number of distribution centers. The Physical Internet introduces hyperconnected distribution systems that are built upon the exploitation of open distribution centers. The openness here refers to using the distribution space and technologies of enterprises offering their services on the market. This paper aims to investigate the economic performance gain at the strategic level by exploiting the hyperconnected distribution system compared to dedicated system. To this end, the distribution-related economic activities of several business samples are modeled by designing their distribution network. Offering several market service scenarios, the distribution network of each business is created for each distribution system. The findings of our investigation demonstrate a highly significant financial gain by exploiting the hyperconnected distribution system, particularly in fast response time scenarios.

Keywords: Distribution system, Hyperconnected Distribution, Dedicated Distribution, Physical Internet, Distribution Network Design, Optimization

1 Introduction

We define a distribution system as both the logical and physical manifestation of all strategies, decisions and operations intended for deployment, storage, handling and delivery of products to clients. The vast majority of the current distribution systems can be categorizes as dedicated, where the distribution facilities, operations and their associated costs are attributed to a single business. The recently introduced Physical Internet (PI) offers a breakthrough vision about distribution systems, called hyperconnected [1],[2]. According to Montreuil [3], a system is said to be hyperconnected when its components (agents, products, etc.) are intensely interconnected on multiple layers, ultimately anytime, anywhere. These layers notably include digital, physical, operational, business, legal and personal interconnectivity. From a logistics perspective, it can ease the storage and movement of physical entities within a system created upon open logistics facilities, capacities and technologies, not restricted to the business owning them but rather offering services to numerous businesses as needed. For instance, an open distribution center is owned by an individual firm while its capacity and technologies are partially or entirely open to be used by other companies, as long as the users are PI-certified, notably for efficiency and security purposes. Note that the same phenomenon applies to transportation. Thus, hyperconnected transportation system consists of open hubs and transportation fleet, which can be openly exploited in multimodal relay mode by other PI-users beyond their owners.

This paper particularly looks into the strategic potential performance gain by exploiting a hyperconnected distribution system comparing to the dedicated distribution system. Thus, it is presumed that the Physical Internet is fully functional and hyperconnected distribution system exists. Taking transportation into account, four systems are defined: dedicated transportation and distribution, dedicated transportation and hyperconnected distribution, hyperconnected transportation and dedicated distribution, and hyperconnected transportation and distribution.

Applying network modeling, the economic activities associated with each distribution system can be investigated [4]. Thus, here a distribution system is modeled and demonstrated by its distribution network. The term web [5] is used instead of network when entities of a distribution network are attributed to more than one business. For example, Figures 1-a, b, c distinguish the disconnected dedicated distribution networks of businesses A and B versus the hyperconnected distribution web exploited by businesses A and B in Figure 1-d.

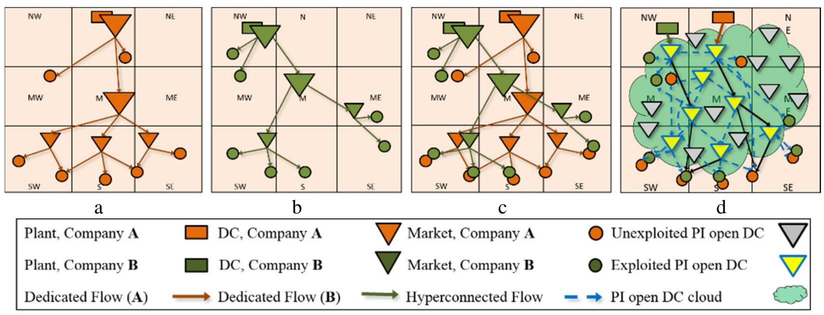

Fig 1. Schematic contrast of dedicated and hyperconnected distribution systems (Adapted from [1])

Our optimization-based investigation methodology involves two main steps. First is to develop a core network design model from which, two system-driven models are developed. Second is to solve the system-driven models for several business cases in order to provide an exploratory assessment of the potential performance gain. Section 2 and 3 describe the mathematical models, business cases and numerical results of our experimentation. Section 4 synthesizes the value contribution of the paper, discusses its limitations and provides future research avenues.

2 The Distribution Network Design Model

2.1 Business Context

The business context studied in this paper is related to the distribution of finished products, starting from a source, called plant. The market location is centralized on the most populated city of a geographical zone (state/province), called market zone. Let $p \in P$ denote a plant, $z \in Z$ a market zone, $l \in L$ a potential distribution center and $g \in G$ a DC capacity and technology configuration. DCs are to be echelon-characterized. First-echelon DCs (e-1 DC) are supplied by the plant and they keep a higher level of inventory (e.g. monthly, seasonal). Second echelon DCs (e-2 DC) are supplied by e-1 DCs and keep lower buffer inventories (e.g. bi-weekly or weekly).

Market zones differ in terms of required service level (SL), here measured in terms of response time (e.g. in days). Similar to [7] and [8], the SL requirements are implemented in the mathematical model by ensuring a maximum distance between a DC and a market zone. Hence, L_z, Z_l represent the subsets of DCs eligible to supply the market zone z and the subset of market zones eligible to be served by DC l, respectively. In this paper, market zones are classified to A, B and C according to their annual demand, which should be completely satisfied. The service level offered to each market is correlated to their classification (i.e. markets in class A with higher demand are offered higher service, meaning shorter delivery times).

The distribution network links represent the transportation flow from plant to e-1 DC, e-1 DC to e-2 DC and e-1 or e-2 DC to a market zone. No lateral transshipment between DCs of the same echelon is allowed. Road transportation by truck is the only transportation mode taken into account. However, three dedicated shipment options are modeled; Truckload (TL), Multi-drop Truckload (MTL), Less than Truckload (LTL). The TL and MTL refer to a fully loaded truck; however, TL travels a direct origin-destination route while MTL operates a route from a single origin to multiple destinations. Knowing that each market zone represents a group of markets (e.g. cities located in a province), the MTL shipment is modeled here particularly for the outbound flows whose quantities are as large as full truck. LTL relates to small size shipments, which incur lower costs if outsourced to less than truckload carriers do. Exploiting the hyperconnected transportation system has no limit on the minimum quantity to be shipped.

2.2 Core Model

The model introduced in this section allows optimizing the distribution network design for each of the alternative distribution systems in terms of economic performance from the perspective of a specific user business. The model parameters and decision variables are as follows:

b_g : Storage capacity at DC configuration g

b_p : Production capacity at plant p

c_{lg}^{o} : Opening and warehousing costs associated with required space at DC *l* at configuration *g* over the planning horizon
c_{l}^{i} : Inventory cost at DC *l* over the planning horizon
$c_{m}^{t}(T_{nn'}^{m}, \delta_{nn'})$: Transportation cost by shipment option *m* from node *n* to *n'* corresponding to the quantity $T_{nn'}^{m}$ and distance $\delta_{nn'}$
d_{z} : Demand at market zone *z* over the planning horizon
f_{e}^{b} : Throughput-to-inventory conversion factor at echelon *e*
f_{lz}^{c} : The load consolidation opportunity factor from DC *l* to market zone *z*
f^{i} : Average inventory to maximum storage capacity conversion factor
M : Very large number
q : Maximum number of pallets allowed in a truck
W : Number of workdays in the planning horizon
$A_{pl}^{TL}, A_{ll'}^{TL}, A_{lz}^{MTL}$: Binary variable equal to 1 if shipment option TL is selected from plant *p* to DC *l*, from DC *l* to DC *l'* and if shipment option MTL is chosen from DC *l* to market zone *z* and zero otherwise
O_{lg}^{e} : Binary variable equal to 1 if DC *l* is opened at echelon *e*, configuration *g* and zero otherwise
$T_{pl}^{m}, T_{ll'}^{m}, T_{lz}^{m}$: Quantity of products transported by shipment option *m* from plant *p* to DC *l*, from DC *l* to DC *l'* and from DC *l* to market zone *z* over the horizon
I_{l} : Average inventory level at DC *l* over the planning horizon

The distribution network design model minimizes the Total Distribution Cost (TDC) (1) over the planning horizon subject to constraint sets (2) to (18).

$$TDC = Min\left(\begin{array}{l} \sum_{l,g} c_{lg}^{o} O_{lg}^{e} + \sum_{l} c_{l}^{i} I_{l} + \\ \sum_{p,l,m} c_{m}^{t}\ (T_{pl}^{m}, \delta_{pl}) + \sum_{l\in L, l'\in L-\{l\}, m} c_{m}^{t}\ (T_{ll'}^{m}, \delta_{ll'}) + \sum_{l, z\in Z_{l}, m} c_{m}^{t}\ (T_{lz}^{m}, \delta_{lz}) \end{array} \right) \quad \textbf{(1)}$$

Subject to:

$$\sum_{e,g} O_{lg}^{e} \le 1 \qquad \forall\, l \in L \quad \textbf{(2)}$$

$$\sum_{z,m} T_{lz}^{m} \le N \sum_{e,g} O_{lg}^{e} \qquad \forall\, l \in L \quad \textbf{(3)}$$

$$\sum_{p,m} T_{pl}^{m} \le N \sum_{g} O_{lg}^{1} \qquad \forall\, l \in L \quad \textbf{(4)}$$

$$\sum_{l'\in L-\{l\},m} T_{ll'}^{m} \le N \sum_{g} O_{lg}^{1} \qquad \forall\, l \in L \quad \textbf{(5)}$$

$$\sum_{l'\in L-\{l\},m} T_{l'l}^{m} \le N \sum_{g} O_{lg}^{2} \qquad \forall\, l \in L \quad \textbf{(6)}$$

$$\sum_{l\in L_{z},m} T_{lz}^{m} = d_{z} \qquad \forall\, z \in Z \quad \textbf{(7)}$$

$$\sum_{p,m} T_{pl}^{m} + \sum_{l'\in L-\{l\},m} T_{l'l}^{m} = \sum_{l'\in L-\{l\},m} T_{ll'}^{m} + \sum_{z,m} T_{lz}^{m} \qquad \forall\, l \in L \quad \textbf{(8)}$$

$$T_{pl}^{TL} \le N A_{pl}^{TL} \qquad \forall l \in L, p \in P \quad \textbf{(9)}$$

$$T_{ll'}^{TL} \le N A_{ll'}^{TL} \qquad \forall l \in L, l' \in L-\{l\} \quad \textbf{(10)}$$

$$T_{lz}^{MTL} \le NA_{lz}^{MTL} \qquad \forall l \in L, z \in Z_l \quad \textbf{(11)}$$

$$qwA_{pl}^{TL} \le T_{pl}^{TL} \qquad \forall l \in L, p \in P \quad \textbf{(12)}$$

$$qwA_{ll'}^{TL} \le T_{ll'}^{TL} \qquad \forall l \in L, l' \in L - \{l\} \quad \textbf{(13)}$$

$$qwf_{lz}^{c} A_{lz}^{MTL} \le T_{lz}^{MTL} \qquad \forall l \in L, z \in Z_l \quad \textbf{(14)}$$

$$f_{e=1}^{b} \sum_{p,m} T_{pl}^{m} + f_{e=2}^{b} \sum_{l',m} T_{l'l}^{m} \le I_l \qquad \forall l \in L \quad \textbf{(15)}$$

$$I_l \le \sum_{e,g} f^{i} b_g O_{lg}^{e} \qquad \forall l \in L \quad \textbf{(16)}$$

$$\sum_{l,m} T_{pl}^{m} \le b_p \qquad \forall p \in P \quad \textbf{(17)}$$

$$O_{lg}^{e}, A_{pl}^{TL}, A_{ll'}^{TL}, A_{lz}^{MTL} \in \{0,1\}, T_{pl}^{m}, T_{ll'}^{m}, T_{lz}^{m}, I_l \ge 0 \quad \forall e \in E, g \in G, l \in L, m \in M, p \in P, z \in Z \quad \textbf{(18)}$$

The objective function (1) minimizes the total distribution cost associated with the distribution network design. Constraints (2) guarantee that each DC is opened, providing a single echelon mission. Constraints (3) ensure that market zones can be allocated only to the DCs, which are already opened. Constraints (4) ensure that only e-1 DCs are sourced from the plant. Constraints (5) indicate that DCs supplying other DCs are first echelon. Similarly, constraints (6) identify DCs sourced by other DC(s) as the second echelon. These two constraint sets are necessary to avoid transshipment among DCs of the same echelon. Constraints (7) ensure that market demand is completely satisfied. Assuming the inventory level at the beginning of the horizon is equal to the end of horizon inventory, constraints (8) balance the transportation flow to and from a DC. Constraints (9), (10) and (11) guarantee that shipment option TL or MTL is enforced if this shipment option is selected for the corresponding link. Dividing the transportation quantity over the planning horizon to the shipment frequency in constraints sets (12), (13) and (14), the quantity of daily transportation flow is anticipated. TL/ MTL flows are selected if the daily transportation quantity is at least equal to the maximum number of pallets allowed in a full truck. Constraints (15) determine the average inventory level at DC echelon. Constraints (16) determine the minimum required storage space at opened DC. Constraints (17) ensure that the total inbound flow from the plant respects its production capacity. Finally, constraints (18) control the integrality and non-negativity of decision variables.

2.3 System-Driven Models

The system-driven models are developed based on the core distribution network design model, subject to differences in parameter and cost settings related to the DCs and transportation.

In dedicated distribution, the cost parameters for DC opening and warehousing is modeled by applying the impact of economies of scale. Thus, the unitary DC opening and warehousing costs are lower for larger DC-capacity configurations compared to smaller configurations. The set L of potential DCs is the same for both dedicated and hyperconnected distribution. The hyperconnected DC exploitation cost is obtained by assuming that influenced by the implementation of the highly advanced modular technologies in open DCs, material handling operations are performed highly efficiently [9]. Because of such efficiency, the unitary cost of exploiting open DCs (regardless of size) becomes fairly close to the cost of large dedicated DC configurations.

In this paper, the dedicated transportation cost function is simultaneously influenced by economies of scale and distance on the entire network (in contrast to [10] where the economies of scale is reserved for the inbound transportation and the economies of distance, only for the outbound). Hence, the unitary transportation cost for long distance and high quantity shipments are lower than for short distance and low quantity shipments. For simplicity, the nonlinear functions of economies are approximated by piecewise and stepwise functions.

One of the goals of the PI initiative is to enhance the quality of life for logistics workers such as truck drivers [1]. Hence, in hyperconnected transportation, the model imposes not to have drivers travel more than a single-day distance from their hometown, letting them come back home and reunite with their families more often. The multitude of PI-enabled open hubs and terminals and their geographical dispersion allow for short trips in the hyperconnected transportation system. Assuming that this opportunity would be preferred by most of the drivers, and knowing that the open exploitations improve the truck filling rates [11], the unitary hyperconnected transportation cost is set equal to the MTL for a single-day distance.

3 Potential Performance Gain Analysis

Inspired by a Canadian manufacturing company, three businesses cases are generated for investigating the expected performance of the alternative systems. Cost parameters engaged in our model, such as DC opening, warehousing, and full truckload shipment are derived from real data of this Company. Moreover, less than truckload transportation cost is based on the data published by FedEx Service guide report 2013. The market zones correspond for each business to some combination of inland states in the U.S.A. and provinces in Canada, represented by their most populated city. The random location of the plants is in Texas, Pennsylvania and Arizona for businesses 1 to 3. The set of potential DCs includes 40 locations across North America. The annual business throughput varies from 60000 to 155000 Pallets/Year. Demand in each market zone for each business is set as a percentage of its annual throughput according to the zone population ratio multiplied by a diversity factor, uniformly distributed between [0,1]. Finally, three market service scenarios are considered. The service level is set to 1, 2 and 3 day response time respectively to the A, B and C class markets in the top service scenario. The medium and basic service scenarios include 3, 5, 7 and 5, 7 and 10 day response time to the class A, B and C markets respectively. One day response time is here ensured by 650 Km distance limit between DC and market zone [7]. The distribution network of each business is optimally designed for each system according to three service scenarios. Figure 2 summarizes the results obtained.

The first main result from the investigation is the gain dominance of the hyperconnected systems over the dedicated systems and of hyperconnected distribution over hyperconnected transportation for the studied sample. According to our results, the collective total distribution cost of responding to the top service level reduces 10% by exploiting the system with dedicated distribution and hyperconnected transportation in comparison to the dedicated distribution and transportation system. This gain represents almost 16 M$/Year. Alternatively, by switching from the dedicated distribution and transportation system to the system with hyperconnected distribution and dedicated transportation, the gain increases to 31%, that is 47 M$/year. The highest gain of 38%, 58 M$/year, is achieved by switching to hyperconnected distribution and transportation system. For individual businesses within the sample, the gain magnitude from fully dedicated to fully hyperconnected system varies from 35% to 45%, since their annual throughput impacts their benefits from the economies of scale.

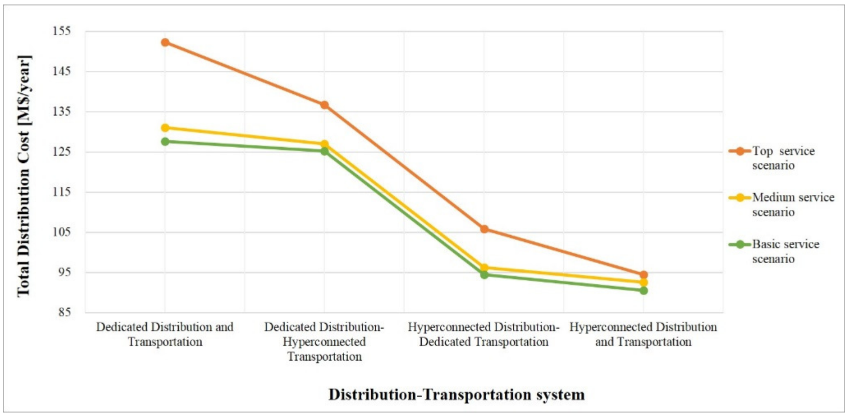

Fig 2. Collective total distribution cost of three businesses cases for each distribution system responding to three service scenarios

The second main result from the investigation is related to the total distribution cost within each distribution system across various service scenarios. As it can be witnessed in Figure 2, in the dedicated distribution system, by offering top service level instead of medium or basic, the total distribution cost increase between 21 and 25 M$/Year. However, once switching to either hyperconnected distribution or transportation, this gap declines to 10-12 M$/Year. With the fully hyperconnected system, the cost of achieving top service level is between 2-4% higher than medium and basic level (correspond to 2-4 M$/year). It can be concluded that offering better service to market can be significantly less expensive by exploiting hyperconnected distribution, notably when combined with hyperconnected transportation.

4 Conclusion

Our goal in this paper was to investigate at a strategic level the potential for economic performance gain from exploiting the recently introduced Physical Internet enabled hyperconnected distribution system. To this end, we modeled the economic activities and optimized the distribution network of three business cases assuming four systems from combinations of dedicated and hyperconnected distribution and transportation. Three sample business cases serving the market zones located in United States and Canada are used for the investigation.

Our findings are highly promising. Hyperconnectivity can reduce significantly the overall distribution costs. In our study, the collective total distribution cost in the hyperconnected system is reduced by 29% to 38% in comparison to the dedicated distribution system responding to the basic and top service scenarios respectively. Moreover, we discovered that providing higher service to markets can be significantly less expensive with hyperconnected distribution (2 to 4% with the fully hyperconnected system, in contrast with 16 to 19% with the fully dedicated system).

Our experimentation has some key limitations, such as single-product business samples and only exploiting truck-based road transportation. In addition, we have only focused on the economic performance gain, while the environmental and social aspects of exploiting the hyperconnected distribution and transportation should be analyzed. Yet the results obtained by this investigation are highly promising and motivating to continue this research avenue, notably tackling the above limitations.

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