



Resilient Hyperconnected Logistics Hub Network Design

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Abstract: Logistics networks frequently face disruptions inducing an increase in delivery costs and delays. This paper studies the design of resilient hyperconnected logistics hub networks for the Physical Internet, modeled as an integer programming problem. The objective is to open logistics hubs in order to connect each origin and destination using multiple minimum length edge-disjoint paths. To estimate the resilience of the designed networks, we propose graphtheoretic measures involving (i) the maximum number of edge-disjoint paths connecting each origin and destination, and (ii) the number of short paths traversing each edge. We develop a case study to design a class of parcel delivery networks in China and evaluate the impact of various disruption scenarios on the resulting distance traveled by parcels. Our results show the relevance of the proposed resilience measures and the increased capability of the designed networks to sustain disruptions in comparison to traditional logistics networks.

Conference Topics: Interconnected freight transportation, logistics and supply networks

Keywords: Hyperconnected Logistics, Parcel Delivery Network, Resilience, Intercity Parcel Delivery, Network Topology, Physical Internet.

1. Introduction

The recent surge in e-commerce and world trade has led the parcel delivery industry to be one of the fastest growing industries (Jin, 2018). In addition, the fierce competition among courier companies motivates the need for fast and convenient delivery of parcels to customers' doorsteps. This propels the industry to be more asset-intensive for quicker parcel delivery to its customers who are spread out across wide geographical regions (Jin, 2018). As a consequence, the industry requires meticulous planning and proper execution. The planning involves strategic decisions such as logistics hub network design and tactical decisions in parcel and vehicle scheduling for timely and resilient parcel delivery.

An extensive research has already been conducted in the domain of logistics hub network design. Several works have studied the hub-and-spoke configuration for logistics hub networks (O'Kelly and Miller, 1994). The configuration is designed based on three assumptions. First, it assumes no direct delivery between the origin and destination nodes. Second, it considers the availability of all possible transportation links between hubs for travel. Last, it assumes a discount factor to model cost savings for routing parcels through the hubs. In the past, researchers have designed logistics hub networks by relaxing one or more of these assumptions but not all (Lin and Chen, 2008; Gelareh et al., 2010; Ben-Ayed, 2013). It has been shown that such a hub-and-spoke network topology does not perform well in high demand scenarios as they may cause congestion of parcels at hubs during peak delivery times (Tu and Montreuil, 2019). Traditional networks constrain flows through two-tier hub-and-spoke structures or force

each hub to be equipped to deal with vast sets of connecting hubs in single-tier point-to-point networks. The lead times, costs, and travel induced by these network topologies are roadblocks toward addressing the efficiency, service capability, resilience, and sustainability challenges faced by the parcel delivery industry (Montreuil et al., 2018). To improve the overall parcel delivery process and to overcome the current limitations, hyperconnected logistics networks are proposed in the Physical Internet (PI) (Montreuil, 2011).

Hyperconnected logistics networks are multi-plane interconnected meshed networks that link open-access hubs present on multiple planes. Together they shape an open network of networks, termed a logistics web (Montreuil et al., 2013, 2018). An initial approach to design multi-plane hyperconnected networks utilized historical demand data and geographical locations as criteria for prospective hub candidates and presented a network flow formulation to select the hubs (Tu and Montreuil, 2019; Ducret, 2014). In PI, these meshed networks can serve as open logistics web infrastructure to be leveraged by the participating players through asset sharing (Montreuil, 2013). Based on this principle, multi-tiered open supply webs have been designed for various purposes such as food distribution, mail delivery, and parcel delivery (Ballot et al., 2012, 2016).

Nevertheless, all logistics networks, including those shaping the PI's logistics web, face disruptions caused by frequent events such as power outages or major traffic jams, as well as low-probability high-impact events such as natural disasters, pandemics, and deliberate attacks. Such disruptions lead to delayed parcel deliveries, increased delivery costs, and excess pressure on functional network components. Considerable efforts have been devoted to gauge the resilience of various logistics and transportation networks in the past. The correlation between structure of the network and its resilience has been showcased through several disruption experiments (Osei-Asamoah and Lownes, 2014). In addition, graph-theoretic measures such as k-shortest path lengths, number of edge-disjoint paths, and node reachability have been utilized to evaluate the resilience of networks (Ip and Wang, 2009, 2011; Herrera et al., 2016). Although these investigations are helpful to assess the resilience of networks, they are rarely used at the network design level (Newman, 2005; Ip and Wang, 2009, 2011; Osei-Asamoah and Lownes, 2014). Some investigations consider disruptions at hubs and transportation links to design a small-scale network (Zhalechian et al., 2018). However, such a small-scale network reveals little to an industry that aims to persistently deliver parcels across a wide geographical region.

This paper proposes an integer programming approach that employs networks' structural properties to design large-scale resilient hyperconnected logistics meshed networks. Specifically, we define the problem of selecting logistics hubs to open in order to connect each origin and destination with multiple edge-disjoint paths of minimum length while ensuring hub hyperconnectivity. This aims to ensure that the network can sustain concurrent edge disruptions that do not induce excessive travel between the origin-destination pairs. In order to estimate the resilience of these networks, we propose two resilience metrics based on network topology that are suitable for the current setting. The first metric analyzes the maximum number of edgedisjoint paths for each origin-destination pair while the second metric studies the number of short paths that traverse each edge. We design multiple resilient logistics networks for the ground transportation and consolidation of parcels in China. In order to evaluate the resilience of the proposed networks, we assess the impact of disruptions on the resulting shortest path lengths in the networks. These disruptions are either random (one or two edges are randomly chosen to be disrupted) or localized (an edge is picked randomly and edges within a specific radius are disrupted). We compare the results of the disruption experiments for the designed networks with those of traditional logistics networks and find that the designed networks have a higher capability to sustain disruptions. Our computational results validate the relevance of the proposed resilience metrics.

The rest of the paper is organized as follows: Section 2 describes the problem setting, formulates the optimization model based on edge-disjoint paths, and presents the resilience measures. In Section 3, we design multiple resilient hyperconnected ground transportation

networks across China for parcel delivery and evaluate their resilience using several edgedisruption experiments. Finally, Section 4 provides concluding remarks and avenues for future research.

2. Problem Definition

We consider a logistics company, a group of such companies, or a territorial authority, that seeks to design a resilient hyperconnected intercity logistics hub network to transport commodities between a set of locations that can be origins O or destinations D for different commodities. Let $\mathcal{P} \subseteq \mathcal{O} \times \mathcal{D}$ denote the set of Origin-Destination (O-D) pairs to be served by opening N logistics hubs among a discrete set of candidate locations, denoted H. We let G = $(O \cup D \cup H, E)$ be the directed graph where E is the set of directed edges $(i, j) \in$ $(O \cup D \cup H)^2$ representing the available transportation links connecting locations i and j. For each O-D pair $p = (s, t) \in \mathcal{P}$, an s - t path $\{s, h_1, \dots, h_n, t\}$ of size n + 2 is a sequence of adjacent nodes starting at node s and ending at node t. In other words, an s - t path starts at s, visits logistics hubs in between by traversing network edges to finally reach destination t. The goal is to select a subset of hub locations $H_o \subseteq H$ with $|H_o| \leq N$ so that the subgraph induced by the set of nodes $(O \cup D \cup H_{\mathbb{P}})$ connects every O-D pair in \mathcal{P} , is efficient in terms of transportation (distance traveled), and is resilient against possible edge disruptions. To this end, we next develop an optimization model based on the k shortest edge-disjoint paths between each O-D pair.

2.1 Integer Programming Formulation

The optimization problem we consider aims to select hubs so as to minimize the total length of the k shortest edge-disjoint paths between each O-D pair in the induced subgraph. We say that k paths are edge-disjoint if no edge is traversed by more than one of the paths. The motivation is that an O-D pair that is connected by several edge-disjoint paths is less likely to be fully disconnected after multiple edge disruptions.

We model this problem as an Integer Program (IP) using an edge-based formulation. For every edge $(i, j) \in E$, we denote its length by $d_{\mathbb{ZP}}$. We consider the binary variables $x_{\mathbb{P}}$ for all $h \in H$ that represent the opened hubs. In addition, we define for every O-D pair $p \in \mathcal{P}$ and every $(i, j) \in E$ the binary variable $f_{i, j}^{p}$ equal to 1 if (i, j) is traversed by one of the k shortest edgedisjoint paths connecting p. Then, the problem can be formulated as follows:

$$\min\sum_{p\in\mathcal{P}}\sum_{(i,j)\in E}d_{ij}f_{ij}^{p}$$
(1)

subject to

$$\sum x_h \le N \tag{2}$$

$$\sum_{\substack{j \in D \cup H \mid (i,t) \in E}}^{n \in H} f_{sj}^p = k, \qquad \forall p = (s,t) \in \mathcal{P}$$

$$\sum_{i \in O \cup H \mid (i,t) \in E} f_{it}^p = k, \qquad \forall p = (s,t) \in \mathcal{P}$$

$$(4)$$

$$\forall p = (s, t) \in \mathcal{P} \tag{4}$$

$$\sum_{i \in O \cup H \mid (i,t) \in E} f_{ij}^p = \sum_{i \in O \cup H \mid \{s,t\}} \forall p = (s,t) \in \mathcal{P}, \forall i \in O \cup D \cup H \setminus \{s,t\}$$
(5)

$$j \in D \cup H|(i,j) \in E \qquad j \in O \cup H|(j,i) \in E$$

$$2 \cdot f_{\mathbb{PP}}^{p} \leq x_{i} + x_{j}, \qquad \forall p \in \mathcal{P}, \forall (i,j) \in E$$

$$f_{\mathbb{PP}}^{p} \in \{0,1\} \qquad \forall p \in \mathcal{P}, \forall (i,j) \in E$$
(6)

 $\forall p \in \mathcal{P}, \forall (i, j) \in E$

 $x_{\mathbb{Z}} \in \{0,1\} \qquad \qquad \forall h \in H.$

Objective (1) minimizes the sum over all O-D pairs $p = (s, t) \in \mathcal{P}$ of the lengths of the k shortest edge-disjoint paths between s and t in the subgraph of G induced by the subset of nodes $O \cup D \cup \{h \in H \mid x_{\mathbb{P}} = 1\}$. Indeed, constraint (2) ensures that at most N logistics hubs are opened while constraints (3)-(5) ensure that k edge-disjoint paths connect each O-D pair. Furthermore, constraints (6) prevent a path from traversing an unopened hub. Therefore, at optimality, the binary variables f indeed represent the k shortest edge-disjoint paths between each O-D pair in the induced subgraph.

2.2 Resilience Measures

To estimate the resilience of logistics hub networks, we consider two graph-theoretic measures. First, we determine for each O-D pair the maximum number of edge-disjoint paths in the network connecting them. This measure indicates the number of simultaneous edge disruptions required to disconnect an O-D pair. In particular, it serves as a proxy to evaluate network robustness: A logistics network with higher number of edge-disjoint paths per O-D pair would be able to handle higher number of concurrent edge disruptions and still maintain its operations.

Second, we define and analyze a new edge-betweenness centrality measure, which computes for each edge $(i, j) \in E$ the fraction of s - t paths, for all $(s, t) \in \mathcal{P}$, of length no more than $(1 + \alpha)$ of the shortest s - t path length that traverse (i, j). The parameter α is a nonnegative number that represents the maximum added distance that the logistics company is willing its commodities to travel. More formally, the edge-betweenness of an edge $(i, j) \in E$ can be expressed as follows:

$$\frac{\sum_{(s,t)\in\mathcal{P}} \binom{\#s-t \text{ paths traversing } (i,j) \text{ of length at most}}{(1+\alpha) \times \text{ shortest } s-t \text{ path length}}}{\sum_{(s,t)\in\mathcal{P}} \binom{\#s-t \text{ paths of length at most}}{(1+\alpha) \times \text{ shortest } s-t \text{ path length}}}.$$

The premise is that, for an O-D pair $(s,t) \in \mathcal{P}$, paths of length more than $(1 + \alpha)$ of the shortest s - t path length induce unnecessary travel and hence will not be utilized for commodity transfer by the logistics company. Therefore, such paths are not relevant in computing the betweenness centrality of an edge. This measure helps us identify the transportation edges that are most critical and that are likely to induce a high increase in travel time if disrupted. A network containing edges with low betweenness centrality is more likely to be resilient to disruptions, as commodities can be rerouted along alternative paths with limited added distance.

3. Computational Analysis

3.1 Case Study Description

We apply the developed methodology to design a resilient hyperconnected intercity parcel logistics hub network to be the backbone infrastructure of China for ground transportation and consolidation of parcels. Core to the Physical Internet spanning China, this network could be leveraged by multiple parcel delivery companies to move numerous millions of parcels every day among Chinese cities. The network is to serve regions that house 93.58% of the Chinese population, are spread across 95.09% of the Chinese inhabitable land, and generate 94.42% of total Chinese GDP (Li et al., 2018). Alternatively, the network topology could also be used by a major logistics provider as an internally shared Physical Intranet.

To design the network, we consider intersections of major highways and existing city-based gateway hubs (inbound/outbound) as candidate locations for intercity hubs (set *H*). These locations help bypass the intracity traffic and probable unnecessary delays. In addition, due to regulations imposed by the Chinese government, a truck driver can drive for 11 hours per day. Hence, we limit the transportation edges $((i, j) \in E)$ to up to 5.5 hours' drive time between locations to enable truck drivers to return home daily while the parcels keep moving toward their destinations.

3.2 Computational Results

By solving the IP formulated in Section 2, with k = 2 edge-disjoint paths for each O-D pair, we designed multiple potential hyperconnected logistics hub networks for different numbers N of logistics hubs to be opened: 70, 80, and 90. The hyperconnected networks with 70 and 90 hubs are shown in Figures 1 and 2, respectively. In these Figures, the yellow asterisks represent regional hubs, and the red lines represent transportation edges between the regional hubs.



Figure 1: IP-based hyperconnected 70-hub logistic network



Figure 2: IP-based hyperconnected 90-hub logistic network

To compare these resilience-optimized hyperconnected logistics networks with traditional ones, we designed lean networks by selecting hubs to open with the goal of minimizing the (single) shortest path length between each O-D pair. Similarly, the transportation edges were limited to 5.5 hours' drive, and the lean networks were generated with the opening of 70, 80, and 90 hubs.

Next, we analyze the resilience measures defined in Section 2.2 for the proposed resilienceoptimized and lean networks. The edge-disjoint path distribution over O-D pairs for both types of networks are depicted in Figure 3. We observe that the proposed networks have a greater number of edge-disjoint paths overall compared to the lean networks. In the lean networks, most of the O-D pairs have at most 3 edge-disjoint paths. This implies that 3 or more concurrent edge disruptions can disconnect several O-D pairs if the lean networks were utilized, while they would have minimal impact on the proposed networks. We find that 5 simultaneous edge disruptions are enough to disconnect all O-D pairs in the lean networks, while the 70-, 80-, and 90-hub resilience-optimized networks respectively require 7, 9, and 10 simultaneous edge disruptions. Furthermore, we observe that as the number of opened hubs increases, the number of edge-disjoint paths increases significantly in the proposed networks are better prepared to sustain a greater number of simultaneous edge disruptions compared to the lean networks.



Figure 3: Edge-disjoint path distribution for the proposed and lean networks

For the edge-betweenness centrality measure, we set $\alpha = 0.2$, i.e., we consider all the paths of length no more than 120% of the corresponding shortest path length. We then compute for each edge the percentage of such paths that traverse that edge. The distribution of this newly defined edge-betweenness centrality measure is depicted in Figure 4. In the 70-, 80-, and 90-hub lean networks, we observe that 78%, 69%, and 74% of the edges, respectively, have betweenness centrality values less than 1%. By comparison, 84%, 87%, and 91% of the edges in the corresponding resilient-optimized networks have betweenness centrality values less than 1%. We note that for the lean networks, the proportion of edges with lower edge-betweenness centrality values remains equivalent as the size of the network increases. In contrast, as we allow more hubs to be opened in the proposed networks, the proportion of edges with low centrality values increases. This suggests that the proposed resilience-optimized networks do leverage the value of opening additional hubs to improve their resilience.

Overall, the lean networks comprise a comparatively greater proportion of edges with high betweenness centrality values. Such edges are critical in keeping the network operational and may cause considerable impact when disrupted. Specifically, the impact includes significant addition in travel time beyond shortest paths, and potential loss of connectivity between O-D pairs. In contrast, the proposed networks have a low proportion of such critical edges, which decreases the chances for high impact during disruptions.



Figure 4: Edge-betweenness centrality distribution for the proposed and lean networks

In order to validate the resilience of the proposed networks, we analyzed the impact of one or multiple disruptions on the networks. In general, non-adversarial disruptions are either random (i.e., arbitrary set of edges is disrupted) or localized (i.e., geographical regions of varied sizes are impacted, and all the transportation edges of the network within the impacted zone are disrupted). Hence, we ran two sets of experiments: (i) random disruptions, where we examined all possibilities of a single edge disruption and two simultaneous edge disruptions; and (ii) localized disruptions, where we examined all the possibilities of a region centralized in one network edge and impacting edges within an impact radius of 0.5 hours, 1 hour, 1.5 hours and 2 hours of travel time, respectively. The metrics used for comparison quantify the average number of disconnected O-D pairs and the average increase in shortest path length for the O-D

pairs that remained connected after each disruption scenario. These metrics provide a comprehensive idea of network performance under disruption. The results of these experiments and the performance comparison with respect to the lean networks are presented in Tables 1 and 2.

The results depict that the lean networks with higher number of hubs maintain better connectivity than lean networks with lower number of hubs. Still, the proposed resilience-optimized networks outperform the lean networks as they guarantee flow of parcels between all the O-D pairs for these disruption scenarios. Importantly the proposed networks achieve this guarantee with lower number of hubs. Furthermore, the additional travel induced by the disruptions in the proposed networks is smaller than in the lean networks. We observe that the increase in the number of simultaneous edge disruptions or in impact radius causes a considerable rise in induced travel and a gradual increase in disconnected O-D pairs for the lean networks. In contrast, the proposed networks worsen at a slower rate as the disruptive impact increases.

The reason for poor performance of lean networks in terms of connectivity of O-D pairs and induced additional travel time can be associated with the presence of edges with higher betweenness centrality values. These edges are critical in nature as they are part of a larger number of short paths for several O-D pairs. When these edges are disrupted, they are most likely to either induce substantial additional travel time or even worse, disconnect O-D pairs. Moreover, the presence of such edges in lean networks of various sizes demonstrates the consistent worse performance for the disruption scenarios. For the proposed resilience-optimized networks, the proportion of higher centrality edges is less, and even lesser as the network size increases. When smaller-centrality edges are disrupted, the impact on the connectivity of O-D pairs and induced additional travel time is insignificant. Hence, the proposed networks are impacted to a smaller extent.

The experiments demonstrate that the proposed network design optimization generates resilient networks that can handle disruptions occurring randomly across their edges, or impacting a localized region, in a better way compared to the lean networks. The results are in tandem with the insights obtained from the topological resilience metrics. Hence, these disruption experiment results validate the proposed resilience metrics.

Disruption Scenario Details	Comparison Metrics	70-Hub Proposed Network	70-Hub Lean Network	80-Hub Proposed Network	80-Hub Lean Network	90-Hub Proposed Network	90-Hub Lean Network
1 Edge disruption	Average # of disconnected O-D pairs	0	0.154	0	0.112	0	0.071
	Average total added length for connected O-D pairs (hrs)	2.370	10.263	5.364	12.917	6.361	9.687
2 Edge disruptions	Average # of disconnected O-D pairs	0	0.316	0	0.228	0	0.146
	Average total added length for connected O-D pairs (hrs)	2.370	10.263	5.364	12.917	6.361	9.687

 Table 1: Simultaneous edge-disruption experiment

Impact Radius	Comparison Metrics	70-Hub Proposed	70-Hub Lean	80-Hub Proposed	80-Hub Lean	90-Hub Proposed	90-Hub Lean
(hrs)	A # -£	Network	Network	Network	Network	Network	Network
0.5	Average # of disconnected O-D pairs	0	0.154	0	0.113	0	0.071
	Average total added length for connected O-D pairs (hrs)	5.573	10.763	5.404	13.802	6.767	10.257
1	Average # of disconnected O-D pairs	0	0.155	0	0.119	0	0.073
	Average total added length for connected O-D pairs (hrs)	6.489	13.381	6.672	17.653	6.855	12.880
1.5	Average # of disconnected O-D pairs	0	0.169	0	0.137	0	0.084
	Average total added length for connected O-D pairs (hrs)	7.625	22.702	8.577	26.541	7.404	17.035
2	Average # of disconnected O-D pairs	0	0.184	0	0.151	0	0.167
	Average total added length for connected O-D pairs (hrs)	7.709	25.505	13.372	32.284	8.933	20.131

Table 2: Localized edge-disruption experiment

4. Conclusion

In this paper we motivate the need for resilient logistics hub networks in the realm of Physical Internet, especially in the parcel delivery industry that is rapidly growing. We formulate an integer program to design a resilient hyperconnected logistics hub network which leverages structural properties of resilient networks, such as edge-disjoint paths. The paper also proposes topological measures to assess the resilience of these logistics hub networks: the maximum number of edge-disjoint paths, for each O-D pair; and a new edge-betweenness centrality measure. While the former measure serves as a proxy to evaluate the network robustness, the latter helps us identify the critical transportation edges whose disruption induces O-D travel time increases.

The devised methodology is applied to develop a resilient logistics hub network across China, which can be utilized by the participating logistics providers in the PI. After conducting random and localized disruption experiments for multiple networks, it can be seen that the generated networks are better equipped to sustain possible disruptions than the traditional logistics networks. In particular, they ensure better connectivity between all O-D pairs and comparatively smaller disruption-induced added travel time than lean networks. These

disruption experiment results are in tandem with the predictions from the proposed resilience measures and hence validate the resilience measures as well.

This paper serves as one of the initial investigations designing resilient networks in the context of Physical Internet, and as such, it opens several avenues for future research. The proposed approach to design resilient hyperconnected network focuses mainly on network topology and can be extended to consider parcel flows, transportation costs, hub capacity, and potential consolidation opportunities. Moreover, examining the resilience of networks under strategic attacks (disruptions) could help in meaningful ways to develop even more resilient logistics hub networks.

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