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Surfing the Physical Internet with Hyperconnected Logistics Networks

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Abstract: *The Physical Internet (PI) presents a transformative vision for logistics systems, where assets are shared openly, and flow consolidation is achieved through standardization, modularization, interfaces, and protocols. Hyperconnected logistics networks have emerged as a promising implementation of the PI, leveraging multi-tier meshed hubs and interconnectivity to achieve greater efficiency, resilience, and sustainability in the transportation of physical goods. However, a lack of clarity in the literature regarding the definition and design of hyperconnected logistics networks presents a significant obstacle to realizing their full potential. To address this gap, we propose a comprehensive definitional framework that integrates key concepts such as tiered network topology, hub interconnectivity, consolidation, and containerization. Moreover, we present a practical design approach for a hyperconnected logistics network in the United States, utilizing a representative demand scenario and accompanying network visualizations to enhance comprehension. Our research aims to unlock the potential of hyperconnected logistics networks as a crucial component of the PI, offering significant benefits to the global logistics industry and society as a whole.*

Keywords: *Physical Internet; Hyperconnected Logistics; Freight Transport; Logistics Network Design; Logistic Hubs; Supply Networks; Network Design; Material Handling; Modularization; Containerization; Omnichannel; E-Commerce Logistics; Modelling; Simulation.*

Conference Topic(s): *networks; interconnected freight transport; logistics and supply networks; material handling; Modularization; omnichannel & e-commerce logistics; manufacturing networks; PI fundamentals and constituents; PI impacts; PI implementation; ports, airports and hubs; vehicles and transshipment technologies.*

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

1 Introduction

The global logistics market is projected to reach about $13 trillion in 2027 [1], currently contributing to about 12% of the global GDP. However, it deals with serious issues pertaining to sustainability, resilience, and efficiency. The transport and logistics sector contributes to about 24% of global carbon emissions and is projected to go up to 40% if strong and effective actions are not taken [2]. Majority of emissions in the logistics industry arise from low truck fill rate of 40-60%, arising from inefficiencies in network design, routing of physical objects, scheduling of vehicles, etc., coupled with the internal combustion engine technology. Vehicles travel long distances resulting in long working hours and away-from-home journeys, leading to a shortage of truck drivers. Products sit at facilities for a long time leading to a loss of speed

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This work does not relate to the authors' position at Amazon.

due to poor consolidation and material handling. Supply chain and logistics networks are highly susceptible to uncertainties and disruptions due to lack of resilience considerations.

The Physical Internet was introduced by Montreuil (2011) to tackle these problems, leveraging as a metaphor of the Digital Internet and its multitude of induced innovations. The Physical Internet (PI) is a hyperconnected logistics system that enables open asset sharing and flow consolidation through standardized encapsulation, modularization, protocols, and interfaces, to improve the capability, efficiency, resilience, and sustainability of serving humanity's demand for physical objects [Montreuil (2020)]. A hyperconnected logistics system comprises layers of cluster networks, service networks, resource networks, mobility networks, stakeholder networks, cyber-physical networks, and governance networks [Crainic, Klibi, Montreuil (2023)]. In this paper, we focus on the first three layers.

Traditional network topologies are formed by a mix of hub-and-spoke topology across layers, and a point-to-point topology within the layers. A hub-and-spoke network topology lacks resilience in cases of hub-based disruptions such as strikes, attacks, and demand overloads, or arc-based disruptions such as highway closures. A point-to-point network topology, where hubs can be connected to all other hubs, results in long distances traveled by vehicles resulting in long working hours for drivers, and poor consolidation of goods resulting in low fill rates. A hyperconnected network topology that results from cluster, resource, service, and mobility networks has the potential to improve efficiency, sustainability, resilience, and capability of logistics networks.

This paper provides a comprehensive definitional framework for hyperconnected logistics networks, primarily covering aspects of topology and consolidation. We review the literature on this topic and explain the concept by showing a hyperconnected network for simple examples of uniform and radial demand distributions. We then present an approach for designing a hyperconnected logistics network for a representative demand distribution in the United States. We describe the design approach for multi-tier cluster networks, hub networks, and meshed networks. Our visualizations of the multi-tier networks provide a compelling vision of an essential aspect of the PI. We argue why hyperconnected logistics networks can outperform traditional networks and conclude by highlighting several open research questions involved in their design. Our research aims to contribute to the development of sustainable, resilient, and efficient transportation of physical objects, which has significant implications for the logistics industry and society as a whole.

1.1 Literature Review

Beyond the conceptual Physical Internet pillars (e.g., Montreuil, 2011; Montreuil, Meller, Ballot, 2013), Crainic et al. (2016) introduce the notion of Hyperconnected City Logistics for applying the Physical Internet in urban logistics environments, notably addressing interconnectivity between cities as nodes of the logistics web, and interconnectivity of city logistics shareholders into an open system. Montreuil et al. (2018) leverage hyperconnectivity as a key concept in leveraging PI in parcel logistic network design, introducing notions such as multi-tier pixelization of space and multi-plane parcel logistics web. They propose removing the hub-and-spoke constraint, and instead propose interconnecting hubs with many more flow options through and between plane-specific logistic mesh networks to enable swift and efficient parcel travel and consolidation. Parcels or sets of parcels consolidated in modular containers are proposed to have a dynamically optimized route, which enables to know the next hub in the route, given a current hub. For logistics networks where the origin of the parcel is fixed at order time (such as UPS, FedEx, SF Express, etc.), individual parcels are to be consolidated early in their journey mostly at access hubs and local hubs, and rarely at gateway hubs, inter-regional hubs, and global hubs. There has been significant research in modeling of two-echelon networks in vehicle routing, facility location, and network design, however multi-echelon logistic networks that are more relevant for solving the problems has been studied by very few [Savelsbergh et al. 2016].

Shaikh et al. (2021) provides a conceptual framework for the transportation of packages in a hyperconnected network, touching concepts of mesh network, dynamic package routing, dynamic containerized consolidation, inter-hub shuttling, and open protocols. In the space of multi-tier mesh networks, there has been some preliminary research on clustering of unit zones to form local cells. Tu et al. (2019) introduces a greedy algorithm, ensuring proximity and demand balance across clusters in the objective function. Hettle et al. (2021) further introduces an optimization-based approach for the clustering task, given locations of local hubs. Muthukrishnan et al. (2021) develops an optimization-based approach for identifying potential locations for access hubs once the unit zones are created. Faugere et al. (2020) provides an example of access hubs in the form of smart locker banks and their design optimization strategies. Several contributions in the literature, such as Campos et al. 2021 and Kaboudvand et al. (2021), focus on hyperconnected logistic network simulator development and simulation-based experimentation, embedding software agents for demand generation, network design, parcel routing and consolidation, service offering, etc.

Since economies of scale play a crucial role in improving efficiency of transportation and logistics systems, PI pushes for open cooperation and collaboration between organizations. Carriers can consolidate their loads and improve their service levels, Hezarkhani et al. (2021) provides an overview of cooperative game theory approaches for designing cost sharing schemes. Several other features of a hyperconnected network that make its implementation successful are real-time monitoring, integration in an information sharing platform, and collaborative decision support systems.

Although there is vast literature on classical network design problems, as described in Crainic, Gendreau, Gendron (2021), stochasticity is generally difficult to deal with in large-scale optimization problems. Literature on hub location seldom considers stochasticity, resilience, or robustness to threats (e.g., Ortiz-Astorquiza et al. (2018)). A hyperconnected framework for pixelization, hub location, and network design, incorporates such considerations in the design. Despite the tremendous progress in research on hyperconnected networks, missing is a framework for defining hyperconnected networks, which this paper intends to provide.

1.2 Hyperconnected Network as Multi-Tier Meshed Network

In framing the applicability of PI-enabled logistics web in the context of city logistics, Montreuil et al. (2018) propose the design of interconnected multi-tier meshed networks and of multi-plane territorial cluster networks. They illustrate the concepts through interconnected six-plane cluster networks and five-tier hub networks. For territorial clustering, customer locations (plane 0) are proposed to be clustered into unit zones (plane 1). Multiple neighboring unit zones get clustered into a local cell (plane 2), multiple local cells into an area (plane 3), multiple areas into a region (plane 4), multiple regions into a block (plane 5), and multiple blocks into our planetary world (plane 6). The facilities in the hub resource network tiers match with the multi-plane spatial cluster network: Tier-1 access hubs are networked in plane 1, then similarly for tier-2 local hubs, tier-3 gateway hubs, tier-4 inter-regional hubs, tier-5 global hubs, and eventually tier-6 earth-planetary hubs. The hubs in each tier are interconnected with neighboring hubs in the same tier, as well as to nearby hubs in the tier directly above and the tier directly below.

The purpose of access hubs is to provide immediate access to neighboring unit zones and are interconnected through streets and roads. They are first/last mile hubs that can for example be smart lockers or mobile trailers. The purpose of local hubs is to consolidate and ease flow in and between neighboring local cells. The purpose of gateway hubs is to connect neighboring areas. The purpose of inter-regional hubs is to connect regions. The purpose of global hubs is to interconnect blocks. They are import and export hubs that have specific processes for customs and security compliance. Flow between hubs leverages transport modes through airways (from drones to airplanes), roadways (from streets to highways), railways, subways, and waterways (from rivers and channels to oceans), including private and public transit systems as pertinent, and depending notably on scale, location, density, and availability.

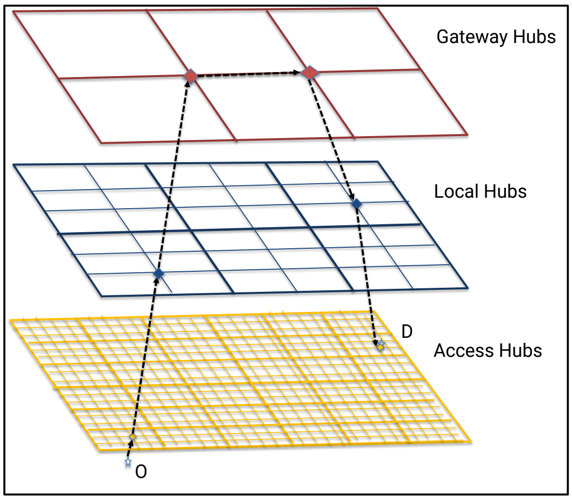

Figure 1: Illustrating flow of goods in hyperconnected networks with uniform demand distribution in a grid space

Figures 1 and 2 illustrate the flow of containerized goods in hyperconnected logistic networks. In a rectangular space, assuming uniformly distributed transport demand, we can structure the space in rectilinear grid fashion as shown for a simple example with three tiers in Figure 1. Each pixel in the bottom, middle, and top tiers respectively denotes a unit zone, a local cell, and an area. At the corners joining pixels in the bottom, middle, and top tiers are respectively located access hubs, local hubs, and gateway hubs. The path of goods depends on the relative location of origin (O) and destination (D), both in specific unit zones at the bottom pixel. Through their path, all goods travel is done consolidated in modular containers (Montreuil et al., 2016). Goods start their journey at O. If O and D are in the same unit zone, goods are shipped directly through some dynamic route. If O and D are in distinct unit zones within the same local cell, then the goods go to an access hub at one of the corners of the origin unit zone (bottom pixel), where they are consolidated towards the access hub most convenient for D, and shipped to D once the goods have reached this access hub. If O and D are in different local cells, they either climb to a local hub at the corner of the local cell or go directly to the D access hub if more convenient when near the origin local cell. At a local hub, if D is in a different area, goods climb to a gateway hub at one of the corners of the area. If D is in the same area, they go to another local hub within the same area. If D is in neighboring local cells, they go down to an access hub in neighboring local cells. Similarly, at a gateway hub, goods either go to another gateway hub within the same region or go down to a local hub in neighboring areas.

Similarly, Figure 2 part (a) illustrates the flow of goods in a hyperconnected network for city logistics with radial pixelization for uniformly distributed demand. Figure 2 part (b) and (c) illustrate ways of pixelization for radially distributed demand in cities, varying inversely with square of radius. This leads to the next question: how to structure the space and create a hyperconnected network for a general demand distribution? Section 2 addresses this question.

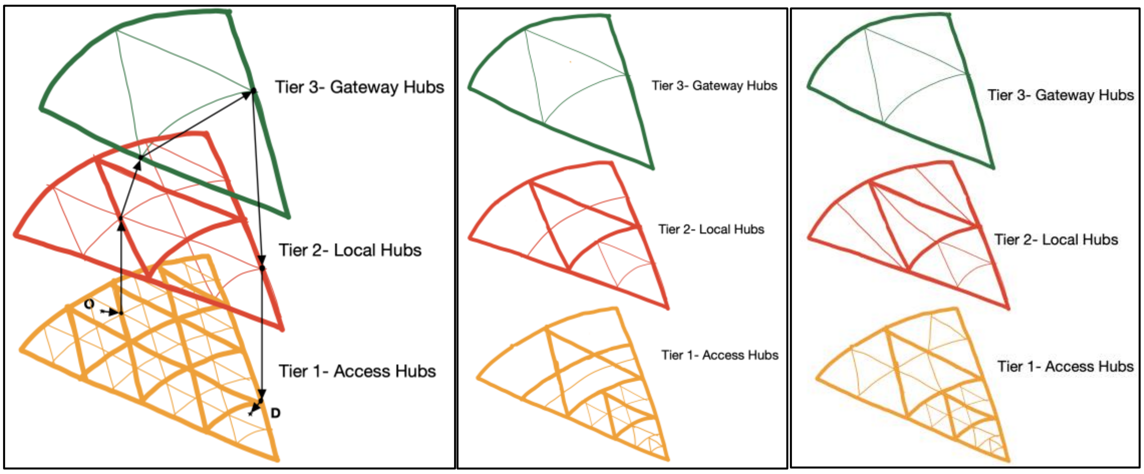

Figure 2: Flow of goods in a hyperconnected network for city logistics with radial pixelization under (a) uniform demand distribution, (b),(c) radial demand distribution varying inversely with square of radius.

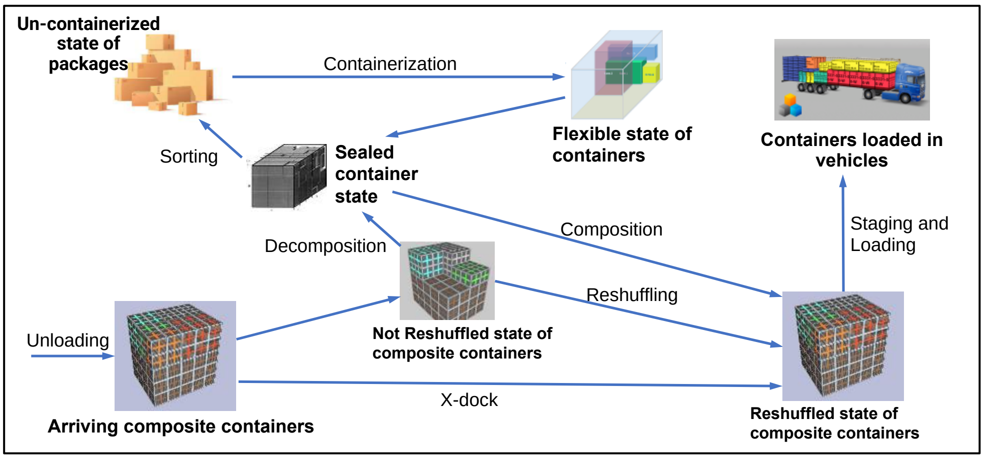

Figure 3: Processes involved in handling of modular containers at a gateway hub

The hubs in a hyperconnected network also differ in material handling and level of consolidation. Access hubs generally deal with individual shipments. Local hubs are usually the first point of consolidation into modular containers, where individual shipments are consolidated by destination local cell. Gateway hubs majorly deal with shipments that are smartly consolidated in modular containers. These hubs primarily perform the operation of re-shuffling smaller handling containers like totes, into larger handling containers like mobile racks, such that containers going towards the same destination gateway hubs are consolidated (Montreuil, McGinnis, Buckley, 2021). Figure 3 illustrates the processes involved in handling modular containers at a gateway hub. They may also cross-dock containers that are consolidated by destination gateway hub. Regional hubs primarily perform the operation of cross-docking containers. They may also act as driver or trailer switching points and charging points for electric trucks. Global hubs deal with the shipments consolidated heavily in shipping containers, that may change from one mode of transport to another.

2 General Hyperconnected Network Design

In this section, we describe the process of building a hyperconnected network for general demand distribution, and we use population data for the U.S.A. to create a representative demand scenario.

2.1 Hyperconnected Multi-Tier Cluster Network for Pixelization

Following are the considerations involved in the logistic space clustering approach used in this paper, along with the reasons.

1. Contiguity: minimizing transportation cost within each pixel, even when there are variations in demand, and making operations easy to manage.
2. Demand balance across pixels: enabling the hubs located to need nearly the same capacity and throughput.
3. Roadways, highways, railroads, and natural boundaries: connecting each pixel well within itself with proper roadways, highways, and railroads to ensure that points inside the pixel can be reached quickly and efficiently; coinciding cluster boundaries with natural boundaries such as rivers and mountains that reduce reachability.
4. Direction and volume of flow: concentrating high-volume nearby flows within the same pixel to minimize flow between pixels and the induced logistic load at inter-pixel hubs.
5. Compactness: minimizing transit times through ease of intra-pixel circulation.
6. Scalability/Adaptability: remaining efficient and/or being readily adaptable and scalable as urban, peri-urban, and industrial areas grow and evolve.
7. Fairness: considering equitably all pixels, whatever their population, logistic flow, and reachability, notably avoiding creating underserved logistic deserts.

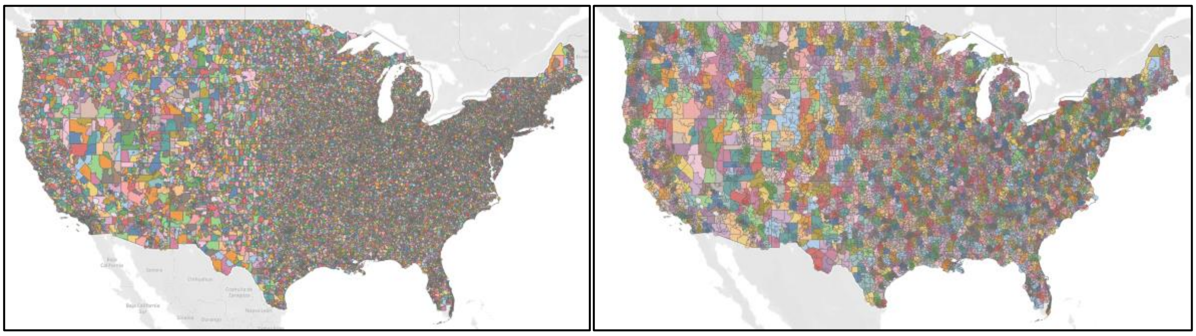

Figure 4: (a) Tier-1 Unit zones and (b) Tier-2 Local cells in a hyperconnected logistics network

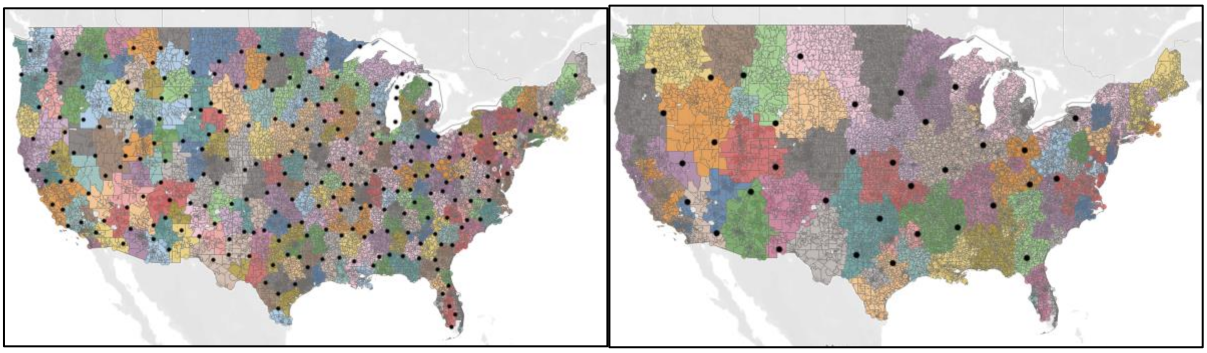

Figure 5: (a) Tier-3 Areas and (b) Tier-4 Regions in a hyperconnected logistics network.

Figures 4 and 5 illustrate the cluster networks in different tiers, with consideration of proximity and demand balance. The maps are not meant to be strictly prescriptive, but rather to facilitate understanding cluster networks and demonstrate their applicability at large scale. From a methodology perspective, proximity-based clustering is done as an initial step to obtain centroids, and an optimization model is used for assignment of pixels to centroids, with a constraint on maximum demand to ensure demand balance across pixels. This is not meant to be a definite prescriptive method, as significant further research is bound to lead to much improved design performance and ease of design.

The plotted cluster networks include 2000 local cells, 300 areas, and 60 regions across the USA. The US 5-digit zip codes have been used for defining unit zones in this illustrative study. This said, we consider that in further studies, the basic definition of unit zones should be challenged, as zip codes were designed for structuring postal services long ago, yet have mostly become fixated, and may not have the most appropriate level of granularity.

2.2 Hyperconnected Multi-Tier Hub Network

The hyperconnected multi-tier hub networks consist of access, local, gateway, inter-regional, and global hubs, which vary by the volume handled, processes involved, and facility designed as described in section 1.2. In a PI paradigm, access to these resources is openly shared as there are multiple cooperating stakeholders from numerous companies.

An interesting location for hubs is the intersection of two or more pixels since it offers efficiency, flexibility, resiliency as lower-tier hubs in the pixel have multiple connectivity options with higher-tier hubs. Black dots in Figure 4, parts (a) and (b), respectively show the potential locations of gateway hubs and regional hubs. These have been obtained from the vertices of a Euclidean distance based Voronoi diagram overlayed on centroids of pixels. A Voronoi diagram is a tessellation pattern in computational geometry, where given a set of finite, distinct, isolated locations in a continuous space, all points in the space are mapped to the closest member of the location set [Boots et al (2009)]. The output is a division of the space into regions, and we use the corners of the regions for locating hubs. We use this because it is a simple method for obtaining approximate intersection points of pixels. We can also have hubs appearing near centers of pixels. This said, real estate access and cost, and traffic, are generally high when very near to high population density, this affects potentially optimal hub locations in practice.

Considerations for creating the tiered hub networks include proximity to higher-tier and lower-tier hubs, and highway intersections for speed of transportation. Megacities have several tiers of hubs within the city. One can have clusters of hubs belonging to the same tier co-located in a proxy location, and some hubs belonging to multiple tiers co-located in the same site. In some networks, locating hubs near ports, and logistics freight corridors also becomes important.

Resilience and robustness to threats are implicitly embedded in the networks of Figures 4 and 5 with the hubs connected as a mesh within a tier and with nearby hubs connected between tiers, as is further described in Section 2.3.

A natural question that arises is how to decide on the number of pixels when there are already facilities that we want to use as hubs in the hyperconnected networks. We use a brownfield analysis for such a scenario and show a simple heuristic approach for Tier-4, inter-regional hubs. When estimating the macro flows through the network, the volume flow across regions can be assumed to be a fraction of the total demand. This fraction would decrease as the size of the region increases. We have assumed this fraction to be concave as a function of the number of regions in the network within a plane. More specifically, we have assumed that this fraction, called average daily inter-regional flow, in terms of percentage of total demand, would be:

$$IRFP = 100 * \left(1 - e^{\frac{1-x}{100}}\right),$$

where, x denotes the number of regions. Shown in Figure 6a, this ensures that the function takes the value zero when there is only one region, is concave, and does not exceed 100%. Since we are locating inter-regional hubs at the intersection of the regions, as we increase the number of regions in the network, the number of tier-4 hubs would also increase. Hence, the average daily volume processed by the hubs would decrease, which we have assumed to be twice the inter-regional flow, divided by the number of inter-regional hubs in the network. We insert the factor two because some goods may be travelling through more than two inter-regional hubs. This gives us a function of average daily volume processed by hubs, with varying number of regions, shown in Figure 6b. From this, we can decide the number of regions we need to create based on the capacity of the existing facilities in the network. Obtaining such a curve using more precise techniques is an interesting area for further research.

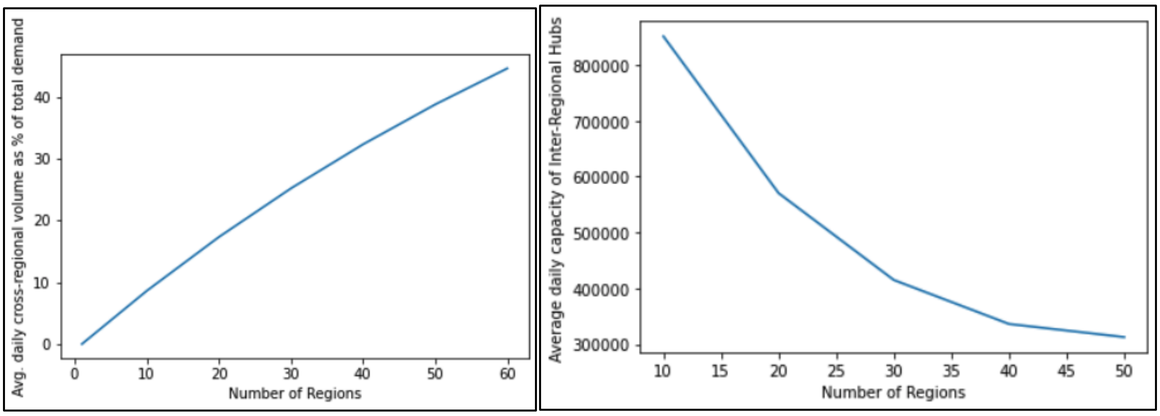

Figure 6: Brownfield analysis for deciding number of regions: (a) Variation of average daily inter-regional volume with increasing number of regions. (b) Capacity required for inter-regional hubs as a function of number of regions.

2.3 Hyperconnected Multi-Tier Meshed Network Design

In a hyperconnected meshed network, there are vertical connections between hubs, i.e., connections between access-local, local-gateway, gateway-inter-regional, inter-regional-global hubs. Hubs in a tier can be connected to hubs in all the neighboring pixels if the connections respect driver regulations. Connections do not skip tiers, for example, access hubs will not directly connect to gateway hubs. Figure 7 illustrates what these connections look like. There are also horizontal connections between hubs in the same tier. Hubs in a tier can be connected to each other if they lie in the same higher-tier pixel as shown in Figure 8, for example, gateway hubs lying in a region, can be connected to each other if the drive time is within regulations. Sometimes, nearby hubs can also be connected across the boundary of the pixel, for example, gateway hubs can be connected to nearby gateway hubs which are in a different region.

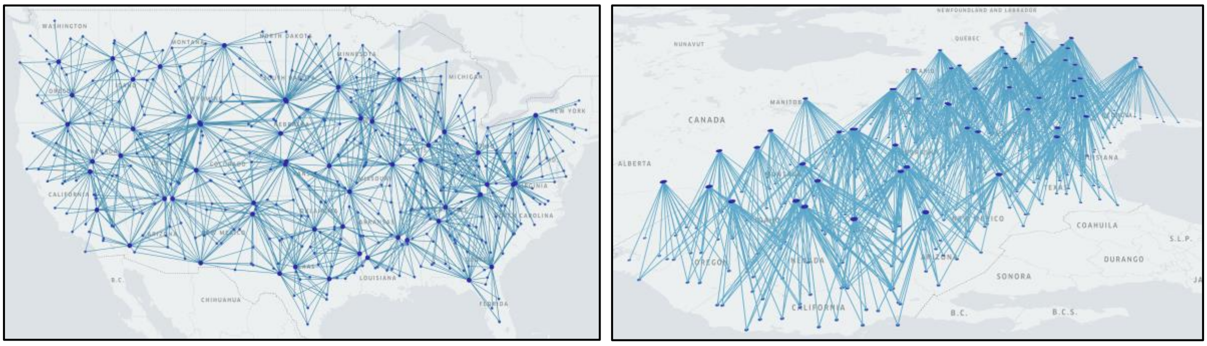

Figure 7: Vertical inter-tier connections between inter-regional hub and gateway hubs shown in (a) 2D, (b) 3D with regional hubs on top tier and gateway hubs at bottom tier, in a hyperconnected network shown for US.

These are all potential connections, and a subset of these connections is to be used for flows associated to any specific shipper. The connections to be used for routing goods on any given day depends on direction and volume of flows, and these potential connections play a role in reducing the size of the network design problem. Once a network is in place, goods are routed dynamically through the network. At each hub in their path, the next hub is decided, notably such that delivery time constraints are satisfied, vehicle fill rate is optimized, and capacity of the hub is accounted for.

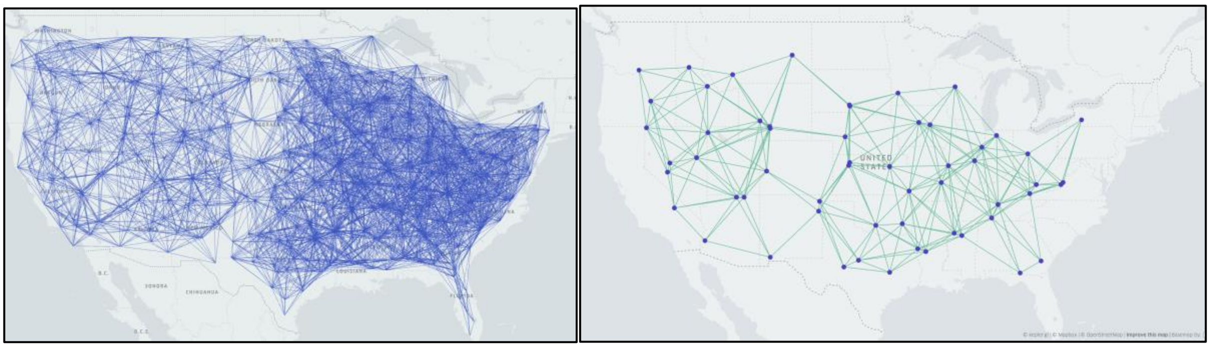

Figure 8: Horizontal same-tier connections between (a) Tier-3 gateway hubs and (b) Tier-4 inter-regional hubs.

3 Conclusion

We have provided a framework for creating hyperconnected logistics networks, starting with a cluster network where we explained considerations for discretizing space. We then described hub networks in specific tiers, and meshed network creation. The hyperconnected networks thus created enable better consolidation when combined with the use of modular containers through the various tiers, as it reduces handling time and efforts at intermediate hubs.

There are several avenues for further research as there are several problems in this framework that can be dealt with using rigorous optimization models. One such example in the cluster network is the problem of defining unit zones as clusters of demand. Beyond zip codes, census blocks can be used for this purpose. Meshed networks can also be defined in further detail by considering flow of goods transferred across regions. Dynamic goods and container routing in a hyperconnected logistics network can be modeled as a sequential decision-making process as at each hub in the journey, goods need to take an action to decide upon next hub from a set of available options, and get a reward depending on level of consolidation. The networks thus created can be tested using simulation with containerized consolidation, to compare against traditional network topologies in important settings. A subject of further research also involves the design and analysis of the network accounting for various types of goods and ownership of hubs. This would involve jointly defining and designing hyperconnected networks for pickup, transportation, and delivery of goods, along with distribution and fulfillment engaged in the deployment of goods.

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