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Enabling Scientific Assessment of Large Scale Hyperconnected Urban Parcel Logistics: System Configuration and Assessment

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Abstract

The complex behavior present in modern logistics systems and the rapid growth of the demand for delivery services are pushing companies towards expanding coverage, improving speed, efficiency, and cost-effectiveness, while building agility, sustainability, and resilience capabilities. Novel approaches such as Physical Internet driven multi-tier hyperconnected networks have been proposed as solutions to these challenges, but their impact and effectiveness are difficult to quantify at the system level. Alternatives for structural system components such as the system topology, the hub network design, operational decision making, and the demand inducing goods flow can define many possible scenarios. Models and tools must be developed to allow these scenarios to be represented and evaluated, enabling design optimization and performance assessment through experimentation. In the context of urban parcel logistics, we present a suite of capabilities required for specifying logistic zones, generating demand scenarios, configuring logistic hubs, developing simulation models, and designing and running experiments, that enables contrast between classical logistic structures and operations and novel implementations such as those using Physical Internet driven hyperconnected infrastructures. The introduction of these capabilities for comparative assessment is meant to serve as a guide, so that robust models can be built towards improving logistics systems performance to meet the increasing challenges for concurrent convenience, speed, efficiency, agility, sustainability, and resilience.

Keywords
Urban Parcel Logistics Systems, Physical Internet, System Configuration, Large-Scale Optimization, Large-Scale Simulation

1. Introduction

As more people, institutions and businesses are inhabiting urban areas, congestion and pollution have become sources of concern, especially in megacities with several million inhabitants. As a result, during the last decade, there has been a growing surge of governmental and citizen engagement for the flow of goods fulfilling urban demand to be achieved sustainably, in harmony with socioeconomic development, quality of citizen life, and environmental friendliness. Concurrently, customer expectations on demand fulfillment have dramatically changed. While same-day delivery was a compelling offer only a few years ago, today's customers are already looking for delivery in less than a few hours within their preferred time windows and locations. These elements have pushed delivery companies towards improving capabilities while optimizing costs. [1]-[4].

Notably, the dedicated Hub-and-Spoke (H&S) logistics network topology described by O'Kelly and Miller [5] which dominated the urban parcel logistics landscape is becoming a delivery-speed bottleneck, as it enforces all parcels to go through big sorting centers, imposing extra travel for nearby origin-destination pairs. Inter-nodal connections and multi-hub assignment have been introduced for improving the performance of H&S networks. The former is a restricted attempt to locally relax the hard network constraints imposed by H&S [6] while the latter is considered mainly as a backup plan in case of hub failure or as a remedy for hub capacity constraints, with minimal emphasis on how it may enable faster delivery [7,8].

This paper specifically addresses urban parcel logistics network design, configuration, operation, and assessment, with a focus on the large-scale networks necessary to serve megacities. It particularly aims to present the main features of a logistics system configuration toolkit, composed by statistical, mathematical and simulation models designed to configure, optimize, and evaluate the system. The toolkit supports specifying and analyzing urban parcel logistics systems, which can be easily extended to generalized logistics systems. This paper aims to be a reference guide for important components to account for while designing systems based on non-conventional H&S network topologies. This assessment is necessary to propose and test innovative system configurations, such as the Physical Internet based multi-tier hyperconnected parcel logistics networks introduced by Montreuil et.al [4].

2. Physical Internet Multi-Tier Hyperconnected Networks

The Physical Internet (PI) was introduced by Montreuil [9] as an innovative logistics system meant to tackle the global logistics grand challenge. It is defined as "an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols" [10]. The Physical Internet concept is materialized through a multi-tier urban parcel logistics web [4], as that shown in Figure 1. This network relies on a five-tier meshing of the world starting at the lowest tier with (1) unit zones, (2) local cells as clusters of unit zones, (3) urban areas as clusters of local cells, (4) regions as clusters of areas, (5) blocks as clusters of regions, with the world being a cluster of blocks. The nodes of the logistics web are logistic hubs enabling the sorting, consolidation, transshipment, and crossdocking of goods.

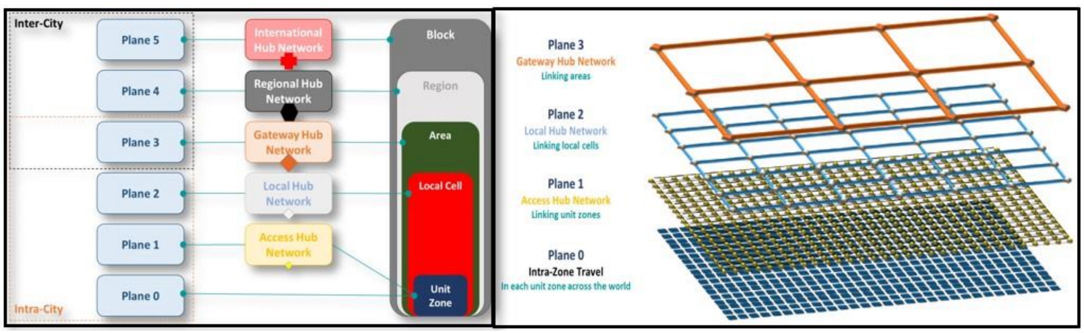

Figure 1: Hyperconnected Logistics Web

In urban environments, access hubs interconnect unit zones, local hubs interconnect local cells, and gateway hubs interconnect urban areas. The hubs may get larger and more advanced in terms of sortation capabilities as we elevate to the higher planes of the logistics web. The parcel movers' size and capacities can be also customized to each tier. In the lower tiers, the inter-hub or hub-to-customer shipments are expected to be executed with light transportation modes such as smaller trucks, vans or scooters; while larger vehicles are to be used for the inter-hub shipment in higher tiers.

Based on the logistics web, Figure 2 shows different network topology connectivity types where (a) represents a hierarchical 3-tier hub-and-spoke network, (b) represents a hierarchical 3-tier hub-and-spoke network with internodal connectivity, and (c) represents the hyperconnected network structure with internodal connectivity. The hyperconnected logistics network is expected to enable an increase in speed and efficiency compared to the traditional hub-and-spoke network topologies, by enabling shortcutting routes for some nearby origin-destinations pairs. Nevertheless, a far more complex level of planning, design, and execution is required with respect to the traditional H&S networks. For instance, parcel routing and vehicle routing, which might be straightforward in H&S networks (Direct dedicated one stop routes), become complex and critical components of the system's operation in the PI hyperconnected implementation, being crucial for enabling speed, cost savings, consolidation, and sustainability.

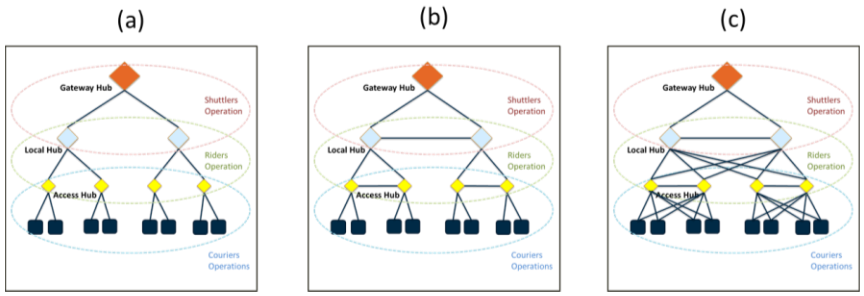

Figure 2: Logistics Network Topology and Connectivity

3. Logistics Systems Configuration

One of the first steps for configuring a logistics system is to understand the flow that moves through the system, i.e., recognize the units of flow that are of interest, when they need to move, where they need to go, and how fast. For urban parcel logistics, the parcels' attributes will drive the system design and operational policies. With this information, some of the main decisions that need to be made are where to allocate logistic hubs, which type of resources to use for moving parcels and how to route them, the requirements of the hubs, and how parcels should be packed and routed through the network. These decisions configure a logistics system, a scenario, which we want to assess and test. Many of these decisions correspond to known problems like clustering, set covering, facility allocation, facility design, sorting planning, resource planning, vehicle routing, and network flows, with the additional complexity added by the fact that many of them interact.

For big enough cities, we can have millions of parcels in a day and thousands of logistic hubs and vehicles interacting altogether, with a fair amount of uncertainty involved. Assessing such large-scale complex systems is a difficult task; therefore, one good tool for tackling this challenge is simulation, which allows modeling all elements of the logistics systems in a digital environment, incorporating uncertainty, computing KPI's, and analyzing multiple scenarios. For this reason, heuristic or alternative approaches defining the system's architecture and operational policies are required so that they can be used inside a simulation model that is meant to run much faster than real life. In this context, embedding complex optimization models for operational decision-making can make the simulation model impossible to run.

4. Logistics Systems Configuration Toolkit

Based on what has been presented so far, this section will describe some of the main tools required to configure and assess a logistics system appropriately. This section is only meant to be a general overview of the features such tools should have and not a detailed description of implemented models. Due to each tool's complexity, independent research work has been published regarding the details and results obtained by each one.

4.1. Generating Demand Scenarios

As parcel flows drive the system's configuration, demand scenario analysis, and customer behavior modeling are critical for ensuring logistic networks' robustness and responsiveness while facing uncertain demand. These models will decide when parcel delivery requests appear in the system, parcel size, destination and delivery speed. For making this happen, the geographical space should be divided into demand space units. There are many ways to divide the space; the most common ones use socio-economic, socio-demographic, and land uses. A classic example of this type of division is the use of zip codes. For the network described in section 2, a simple grid type division can be used for simplicity. An essential feature of this space definition is independence from any logistic topology which operates in such a system. The attributes assigned to each demand grid unit should be sufficient to probabilistically assign demand for all different origin-destination couples through time, defining each customer's delivery time.

The demand generation tool should provide demand logs and probability distributions for demand generation, considering seasonality, trends, and outliers. The seasonality's granularity depends on the level of accuracy required, and for urban parcel delivery systems analysis, hourly seasonality is encouraged. The outputs of this tool should serve as inputs to both the optimization and simulation models described next. To learn more about the detail of Scenario-based Demand generation and Customer Behavior Modeling, see [11]. The model presented describes an AI-based application that contemplates the elements described in this subsection.

4.2. Logistic Zone Clustering

With the demand assigned to grid units, the next step is to cluster these demand units into unit zones, the unit zones into local cells, and the local cells into urban areas. Different objectives can be targeted while solving this problem, such as balancing the demand flow over time in each logistic zone and reducing operational costs. For this matter, an initial set of potential hubs should exist as an input for evaluating the flow costs. It is here where the problems interact, as the clustering depends on the hub network design and the service network design problems. There is a continuous optimization process that must be done between these three problems to obtain good solutions. Heuristic and approximate methods can be used for solving this problem, but we should first try to solve the problem to optimality. An example of an exact solution method is the mixed-integer program described in [12], which incorporates exact contiguity constraints. This model yields the sets of logistics zones to implement.

4.3. Hub Network Design

The hub network design problem comprises two stages: (1) Identification and filtering candidate hub locations, and (2) the hub location problem. Identifying and filtering candidate locations consists of providing methods to reduce candidate location sets' size, ensuring the quality of clustering and network design optimization solutions while fostering scalability and tractability when dealing with large-scale urban agglomerations. To take advantage of the multi-plane hyperconnected system's structural characteristics, all locations on the boundary of unit zones can be used as the initial set of candidate hub locations. Furthermore, these locations can be filtered through an IP-based optimization approach. Depending on the cluster considered, optimization approaches with different objectives can be proposed. For example, a simple IP-based set-covering optimization model can be proposed to minimize the number of candidates, or it can have the objective of minimizing the total operational cost with constraints added enforcing a certain number of hubs to serve the cluster considered.

Having identified candidate hub locations and territorial clustering, the next step is to identify for each cluster a subset of the candidate hub locations, intra-connecting and inter-connecting the set of hubs that have traffic requirements by installing transmission facilities (hubs) at minimum cost. The hub network should be designed such that it is robust and resilient to external events. To enhance networks' robustness against uncertain demand, the concept of modular capacity can be applied by considering hubs with variable modular storage capacity, such that modules can be removed/added/shuffled over the network to balance hub capacity dynamically [13]. When it comes to the network's resilience, we should prevent flow concentration on a single or few hubs in each cluster to minimize the impact in case of a hub/arc disruption. IP-based optimization approaches can be developed to reflect such requirements. An example of the implementation of an exact solution is a variant of an arc-based network flow optimization formulation with constraints enhancing the network's robustness and resilience with the objective of minimizing the total cost, including transportation, hub investment, and operational costs.

4.4. Service Network Design

With a given set of hubs open and all necessary information known to build the service network, the next step is to solve the service network design problem. This problem determines the selection and scheduling of services, specifications of hub operations, and parcels routing to satisfy service levels. The service network design aims to seek a path specifying how parcels will be transported from their origin to their destination and a transportation plan achieving the economic and quality targets. Quality targets concern the reliability of deliveries, meaning the percentage of on-time arrivals. The transportation plan should be able to specify each vehicle's movement, including when it departs its origin and arrives at its destination, which will also imply the dwell time of parcels at each hub.

Optimization-based heuristic and approximate methods can be developed to solve this problem since the pure integer program (IP) cannot be solved in an acceptable amount of time for real-world instances. A feasible heuristic approach to solve the problem is to predetermine the shortest path for each parcel and design a minimum cost transportation schedule for how to transport them based on the shortest paths. Then, some improvement heuristic can be developed to improve the transportation schedule for better consolidation.

4.5. Configuring Logistics Hubs, Parcel Routing, Containerization, and Consolidation

The logistics hubs have different sorting capabilities depending on the tier of the network they serve. For the PI enabled hyperconnected case, smaller hubs should have sorting capabilities, for which the use of technologies such as the internet of things (IoT) and augmented reality will be needed to enable workers at lower network tiers to identify and consolidate parcels quickly. Depending on each hub's required capacity, manual, automated, or mixed sorting strategies can be implemented. Therefore, the number of machines to use, the number of possible sorting destinations per machine, and the personnel required per shift are vital decisions to make; thus, resource scheduling models are encouraged to define these parameters. Also, the complex nature of big hubs' operations might require the use of independent simulations just for these hubs.

For routing parcels through the hubs, an initial feasible path should be assigned for each one. Such a path must be feasible with respect to the parcel's delivery service promise and should aim for consolidation with other flows along its journey. Consolidation refers to integrating disjoint parcels flow, all heading to some joint next destination, into larger volume shipments. The parcels within each shipment are then further grouped into box/tote containers of proper sizes, a process referred to as containerization. Containerized consolidation not only reduces the time and effort spent in material handling and sorting processes (by decreasing the number of parcel touches), but it also reduces the chances of in-transit damages to the parcels. Importantly, containerization can free up sorting capacity at critical hubs as containers bypass the sorting process. Moreover, containerization simplifies handling, loading, and unloading processes at the hubs [4]. These decisions should be made hand in hand, as they mutually affect one another.

Due to the fast-paced evolution of urban logistics systems over time and its inherent uncertainty, there has been a recent trend toward dynamic and live decision protocols, used as needed to make decisions. Such a framework facilitates dynamic adjustments to the parcels routing and consolidation as more information becomes available through the parcel's journey. However, in large-scale urban logistics systems, dynamic (re)routing of parcels considering containerization opportunities with other flows may be challenging. In such settings, taking advantage of the concept of a hyperconnected logistic web, a decentralized decision system based on logistics zones for parcel routing, consolidation, and containerization is recommended. In a decentralized decision system, information is logged and continuously updated locally while remaining globally accessible. Parcels' routes are then created by attaching locally built legs based on global information. The containerization decision is made at each hub with the information over existing and arriving parcels at the hub, their planned route, and the system's overall flow.

4.6. Systems Description

Regardless of how the system is configured, once the initial system setup has been defined, properly describing the system of interest before making any assessment is recommended. This tool should be able to objectively describe all essential aspects of the system independently of the methodology to be used for assessing or configuring the system. There is no consensus about a formal language to use for modeling logistics systems; therefore, each modeler uses a particular way to describe the systems. The system's description should allow all stakeholders to easily intervene in the improvement process, so a formal unified language is proposed for the description process. Among the different languages available for this purpose, we recommend the systems modeling language OMG SysML™, as it allows customizing the language for a specific domain, providing a rich set of fundamental abstractions, and allowing easy computations [14]. This type of methodology is expected to become a common practice in the coming future.

4.7. Developing Simulation Models and Experiments

With the appropriate description of the system, the next step is to build a simulation model to assess the impact of the decisions made for solving problems in sections 4.1 to 4.5. Simulation tools are invaluable for the design, analysis, and management of large-scale logistic systems by allowing to render all operations of such complex. The simulation model should be able to incorporate customer demand at parcel granularity with millions of such demands daily, for flow into, out of, and within a megacity. It also should account for the customers' preferences, routing, scheduling, consolidation, and sortation decisions necessary to deliver the required services.

To better assess a wide range of scenarios, the simulation platform should be designed to be robust while flexible in scale, scope, and decision architecture. One key factor in making a large-scale parcel logistics simulator scalable is decentralizing the controls, the data storage, and queries. The platform should be capable of modeling various system configurations read directly from input files. Finally, the simulator should allow the user to choose between possible decision architectures to formulate multiple experiments, change parameters, analyze network structures, and test decision-making logic towards improving the overall system performance. The design of a holistic parcel logistics system mostly involves more than one simulation technique [15]. A discrete-event agent-based simulation model that suits well large-scale urban parcel logistics systems can be found at [16].

5. Conclusions

Modern logistics systems require continuous assessment and improvement to keep up with globalization's increasing challenges and rapid market growth. Innovative system configurations such as Physical Internet enabled multi-tier hyperconnected networks are being proposed to tackle these challenges. Nevertheless, the system's management increases in complexity for these implementations compared to traditional configurations as the hub and spoke networks. Properly configuring, optimizing, and assessing new logistics systems is a complex task that must be carefully executed to improve systems performance.

This paper describes a set of tools needed to appropriately configure and assess logistics systems, focusing on urban parcel logistics. The tools described are not the only ones required for this process, but they cover the major decisions to be made for operating these systems. The main topics addressed are demand modeling, logistic network design and operation, service network design, hub configuration, containerization, flow consolidation, systems description, and simulation. This document is meant to be used as a guideline for formally configuring, modeling, assessing, and improving logistics systems and reference appropriate research in some of the toolkit models.

References

[1] M. Savelsbergh, and T. Van Woensel, "City Logistics: Challenges and Opportunities," *Transportation Science"*, vol. 50, no. 2, pp. 579-590, 2016.

[2] T. G. Crainic, and B. Montreuil, "Physical internet enabled Hyperconnected City Logistics," *Transportation Research Procedia*, vol. 12, pp. 383-398, 2016.

[3] B. Montreuil, "Omnichannel Business-to-Consumer Logistics and Supply Chains: Towards Hyperconnected Networks and Facilities," in *Proceedings of 14th International Material Handling Research Colloquium*, Karlsruhe, Germany, 2016.

[4] B. Montreuil, S. Buckley, L. Faugere, K. Reem, and S. Derhami, "Urban Parcel Logistics Hub and Network Design: The Impact of Modularity and Hyperconnectivity," in *Proceedings of 15th International Material Handling Research Colloquium*, Savannah, Georgia, USA, 2018.

[5] M. O'Kelly, and H. Miller, "The Hub Network Design Problem - A Review and Synthesis," *Journal of Transport Geography*, vol. 2, no. 1, pp. 31-40, 1994.

[6] K. Lumsden, F. Dallari, and R. Rugger, " Improving the efficiency of the Hub and Spoke system for the SKF European distribution network," *International Journal of Physical Distribution & Logistics Management*, vol. 29 no. 1, pp. 50-66, 1999.

[7] Y. An, Y. Zhang, and B. Zeng, "The reliable hub-and-spoke design problem: Models and algorithms," *Transportation Research Part B: Methodological*, vol. 77(C), pp. 103-122, 2015.

[8] R. Camargo, G. Miranda, R. Ferreira, and H. Luna, "Multiple allocation hub-and-spoke network design under hub congestion," *Computers & Operations Research*, vol. 36, pp. 3097-3106, 2009.

[9] B. Montreuil, "Toward a Physical Internet: meeting the global logistics sustainability grand challenge," *Logistics Research*, vol. 3, pp. 71-87, 2011.

[10] E. Ballot, B. Montreuil, and C. Thivierge, *Functional Design of Physical Internet Facilities: A Road-Rail Hub*, CIRRELT, 2013.

[11] Z. Bahrami Bidoni1, S. Kaboudvand, M. Campos, B. Montreuil, "Enabling Scientific Assessment of Large Scale Hyperconnected Urban Parcel Logistics: Scenario-based Demand and Customer Behavior Modeling," *IISE2021*.

[12] T. Shirabe, "Districting modeling with exact contiguity constraints," *Environment and Planning B: Planning and Design*, vol. 36, pp. 1053-1066, 2009.

[13] L. Faugere, W. Klibi, C. White III, and B. Montreuil, "Dynamic Pooled Capacity Deployment for Urban parcel Logistics", *arXiv preprint arXiv:2007.11270*, 2020.

[14] G. Thiers and L. McGinnis, "Logistics systems modeling and simulation," *Proceedings of the 2011 Winter Simulation Conference (WSC)*, Phoenix, AZ, 2011, pp. 1531-1541.

[15] S. Brailsford, T. Eldabi, M. Kunc, N. Mustafee, and A. Osorio, "Hybrid simulation modelling in operational research: A state-of-the-art review," *European Journal of Operational Research*, vol. 278, pp. 721-737, 2019.

[16] S. Kaboudvand, M. Campos, B. Montreuil, "Enabling Scientific Assessment of Large Scale Hyperconnected Urban Parcel Logistics: Agent-based Simulator Design," *IISE2021*.