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***Abstract:*** *In hyperconnected urban logistics, all components and stakeholders are connected on multiple layers through standardized interfaces and open networks to achieve seamless responsiveness, efficiency, resilience, and sustainability. Key for high performance is achieving coordination and cooperation of urban stakeholders. In this paper, we introduce the design of hyperconnected logistic service networks where associated logistic activities to move flows within an urban city are outsourced to third-party logistic service providers (3PL) via a bidding process to create service networks that are highly responsive and flexible at robustly responding to customer demand. We propose a framework for designing such networks that leverages a reverse combinatorial auction mechanism in which a logistic orchestrator serves as the auctioneer, putting out the logistic activities for auction and a set of participating service providers serve as bidders. We describe the design components of hyperconnected service networks and positions them into a comprehensive 3-stage design-making framework. Finally, we identify promising future research avenues for each stage in the proposed framework.*

***Keywords:*** *Service Network Design; Hyperconnected City Logistics; Physical Internet; Combinatorial Auction*

***Conference Topic(s):*** *networks; interconnected freight transport; distributed intelligence last mile & city logistics; logistics and supply networks; PI fundamentals and constituents; PI impacts; PI implementation; PI modelling and simulation;*

***Physical Internet Roadmap*** *(Link): Select the most relevant area(s) for your paper: ☒ PI Nodes, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Access and Adoption, ☐ Governance.*

## 1 Introduction

As a hyperconnected global logistic system aiming to serve efficiently, resiliently, and sustainably humanity's demand for physical object services, the Physical Internet (PI) enables a logistic web interconnecting multi-plane and multi-party meshed logistic networks serving the multi-tier logistic space (Montreuil et al., 2015). Such networks comprise multiple tiers of logistics hubs (e.g., access hubs (AHs), local hubs (LHs), etc.) and territorial clusters (e.g., unit zones (UZs), local cells (LCs), etc.) adapted to each plane as illustrated in Figure 1. This logistic web allows parcels to flow through each meshed plane using hub and cluster-based transport operations characterized by openly shared access to logistics resources and service outsourcing, increased cooperation and coordination, and information exchange.

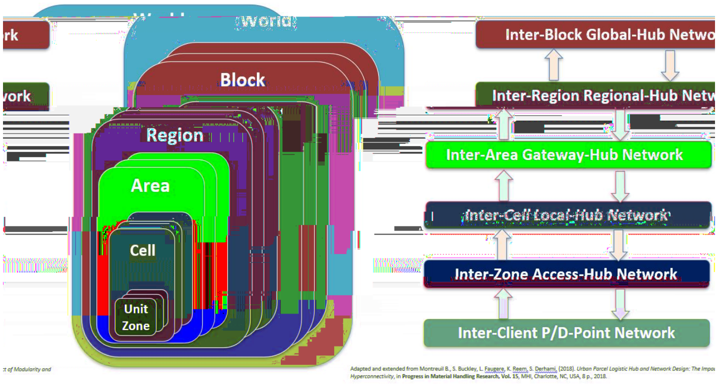


*Figure 1: Multi-Plane Logistic Web Serving the Multi-Tier Logistic Space of the Physical Internet*

Provided with a multi-tier set of interconnected logistic networks, our paper introduces a service network design approach for an urban transport system that outsources to multiple third-party logistic (3PLs) service providers, accounting for customers' expectations to receive fast and reliable services. A fair amount of literature has studied optimizing the design and operations of package express carriers' service networks, but most of the literature has focused on the service network design for intercity package flows rather than urban parcel delivery (Kim et al., 1991; Barnhart et al., 2002; Yildiz et al., 2022). For urban delivery systems, there recently has been several relevant works taking into account key characteristics of intra-city delivery systems. He et al. (2022) and Wu et al. (2023) studied a new service network design problem for an urban same-day delivery system with hub capacity constraints. Most of the service network design research is focused on first-party service network design (Bakir et al., 2021). Literature focused on designing service networks leveraging 3PLs is scarce. In the similar spirit to our paper, there is an extensive amount of literature that studied the application of combinatorial auctions in transportation procurement problem. A review of practical issues related to the execution of combinatorial auctions in transportation service procurement problem can be found in the work by Caplice and Sheffi (2006). Large amount of literature has studied decision-making problems in the combinatorial transportation procurement system from the shipper and carriers' perspective, respectively (Song and Regan (2003); Sheffi (2004); Song and Regan (2005); Guo, et al., (2006); Chen, et al., (2009)). Pan et al. (2014) introduces the use of Mechanism Design theory to make a business model of the logistic service providers where every transport service is auctioned and develops a simulation framework for auction-based transport service allocation process in PI. However, most of the literature does not specifically consider urban context and only considers single origin-destination pairs (i.e., lanes) of demand rather than logistic network perspectives.

Key contributions of our paper are threefold: (1) introducing a new research notion of PI urban logistic service network design where all hub logistic and cluster transport activities are outsourced to 3PL service providers through a combinatorial bidding process; (2) developing a combinatorial auction-based framework enabling to set service level agreements (e.g., time requirements) and determine winning service providers for each logistic activity, and (3) proposing a bidding scheme engaging multiple service providers and expressing price-time trade-offs (in the spirit of D'Amours et al., 1997).

## 2 Framework for Hyperconnected Bidding-Based Logistic Service Network Design

In this section, we introduce the hyperconnected bidding-based logistic service network design problem. We first introduce key decision-making stakeholders involved in designing hyperconnected service networks and discuss what decisions each of these stakeholders must make and what impacts their decisions. We then propose a conceptual design-making framework that leverages a reverse combinatorial auction mechanism to structure the design of such service networks in multi stages.

## 2.1 Problem Definition

We consider a reverse combinatorial auction involving a logistic orchestrator (the auctioneer) who is looking to outsource the logistic activities under its responsibility, and multiple logistic service providers (bidders) looking to win contracts to offer logistic services over a specified future period. We consider as a logistic orchestrator an urban authority, a logistic company, or a set of such organizations that desires to design a hyperconnected service network leveraging service providers via bidding process to timely and robustly transport shipments between a set of predetermined origin-destination (O-D) pairs in a way to minimize total outsourcing cost in a multi-tier set of interconnected logistic networks as illustrated in Figure 2.

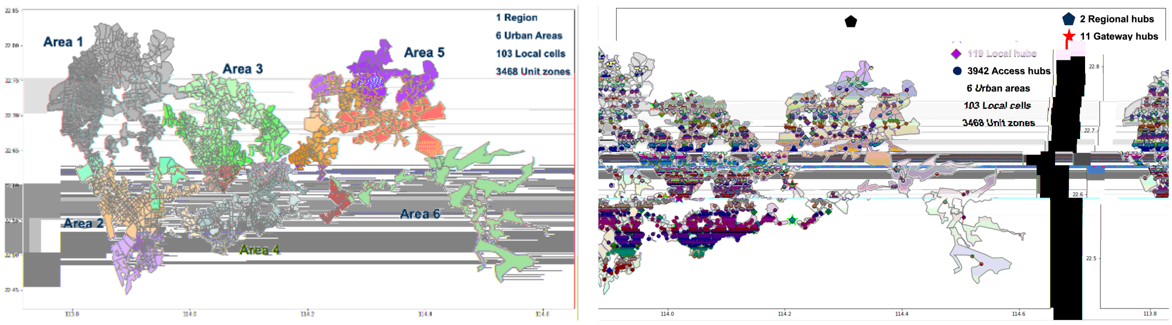


*Figure 2: Hyperconnected Multi-tier Logistic Networks: (Left) Territorial Clusters. (Right) Multi-tier Logistic Hubs*

We assume that the O-D pairs that the orchestrator offers transport services for are grouped into three types of shipments: (1) within-local cell (LC) shipments, (2) within-urban area (UA) shipments, and (3) within-region shipments. For example, within-region shipments travel from their origin to destination across the interlaced mesh networks through multiple planes using hub processing and cluster transport operations. Hub processing operations refer to a set of intra-logistic operations that take place in a hub to handle inbound parcels/containers to be ready for outbound shipment. Cluster transport operations refer to transporting parcels/containers between hubs within a specified territorial cluster as illustrated in Figure 3.

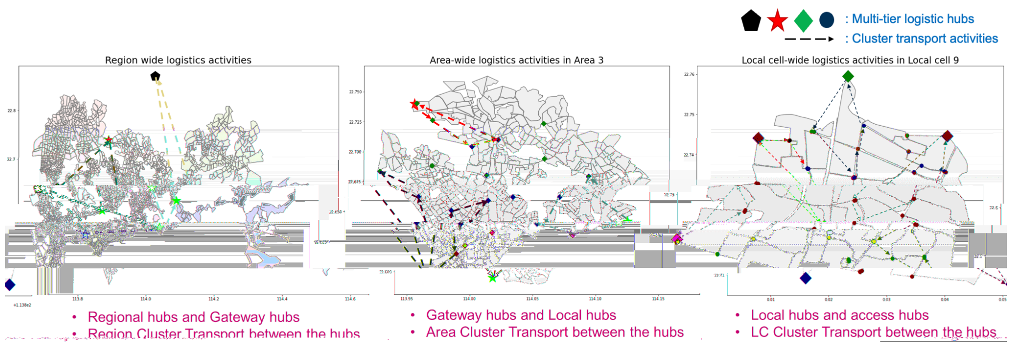


*Figure 3: Logisitc activities in each plane: Region-wide activities (left), area-wide activities (middle), and local cell-wide activities (right)*

We assume that each O-D pair is associated with a predetermined path consisting of a set of logistic hubs and clusters to traverse and is associated with target O-D service guarantees (e.g., 6-hour delivery) to be respected within a target reliability (e.g., 99%). The orchestrator uses standardized bidding languages (e.g., OR/XOR bids) that allow participants to formulate their bids and express bid requirements on their execution. For the bid requirements, the orchestrator specifies service level agreements (SLAs) for each logistic activity (e.g., 30 mins for local cell 1-cluster transport activities) such that the O-D target service guarantees are robustly met. The SLAs can thus be thought of as service capability expectations for service providers.

We consider a set of third-party logistic service providers (3PL) of two types respectively interested in offering services for hub processing and/or cluster transport activities within urban cities. We call such service providers "Bidders" throughout this paper. According to the imposed bidding language, these bidders make their bidding decisions in three stages: (1) they first select which logistic activity(ies) they are to bid on based on highest utility for them among considered activities, (2) then they evaluate what service capability in terms of time they can offer in accordance with the SLAs, and lastly (3) they determine what bid price to offer. Winning bids then result in contracts for the termed horizon (e.g., 3-year), subject to SLA clauses, to ensure persistent performance of the service network.

Given these decision-making stakeholders, as an alternative way to first-party service network design, the proposed research is to develop a design-making framework for designing and planning multi-stakeholder-engaged service networks inspired by the Physical Internet that will be able to robustly offer transport services across the multi-tier networks in a cost minimization manner by considering both the auctioneer's (orchestrator's) and bidders' (service providers') perspectives.

## 2.2 Design of Hyperconnected Logistic Service Networks

We structure the hyperconnected logistic service network design process in three phases which correspond to pre-auction, auction, and post-auction stages as shown in Figure 4, notably leveraging the work of Song (2003) on single round and multi-round combinatorial auctions: (1) Logistic Activity Selection for Auction and Bid Definition/Requirements, (2) Bid Construction, and (3) Bid Assignment.

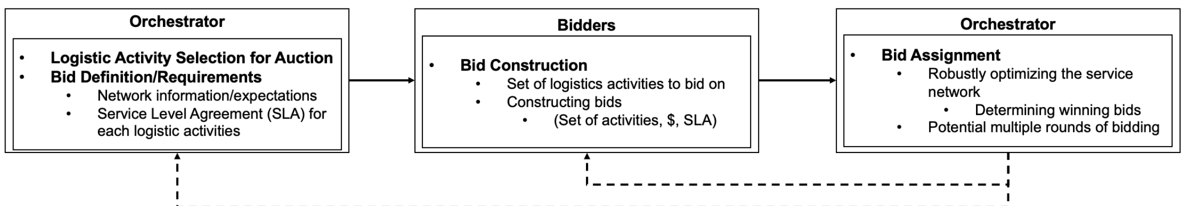


*Figure 4: Proposed Hyperconnected Logistic Service Network Design Process*

### 2.2.1 Phase 1: Logistic Activity Selection for Auction and Bid Definition /Requirements

In Phase 1, during the pre-auction stage, the orchestrator completes the following tasks: (1) forecasting the demand for the upcoming period's needs (e.g., 3-year) and selecting logistic activities for auction and (2) determining what information the bidder is required to submit back and abide by. In other words, the orchestrator collects demand information across the network and analyzes expected demand flow over the logistic activities. Then, they must determine which logistic to be serviced by its own capacity or to be outsourced through auction. The orchesetrator then specifies bidding language that all bidders must use to encode their preferences and bid requirements for SLAs for logistic activities such that bids are defined to contain composite information for a single or set of activities to bid on, corresponding bid price, and service capability.

One of the key considerations that the orchestrator must consider during the pre-auction stage is the process of determining O-D service guarantees to offer across the network and SLAs for logistic activities, as such process impacts the overall business and service costs for outsourcing bidders. Such O-D guarantees can be estimated through simulation with historical data or with synthetic data from benchmarking competitors' service guarantees. Once O-D service guarantees are established for a given set of O-D pair transport services, SLAs for logistic activities must be determined such that each of the O-D service guarantee is met. The orchestator can simply select a combination of SLAs that satisfies O-D service guarantees. However, which SLA(s) the orchestrator imposes on logistic activities significantly impacts the bids that they receive from bidders at Phase 2 (and thus total outsourcing cost obtained at Phase 3). For example, for a given O-D pair-path traversing three logistic planes, one can simply allocate its service guarantee time equally among the planes of the path. However, some planes might expect huge fluctuation in demand, which makes it difficult for bidders to plan in accordance with the imposed SLA and estimate required number of resources, and possibly end up asking a significantly higher bid price as they might need demand scenarios is generated, and each synthetic version of potentially participating bidders is created, equipped with an approximate cost structure (e.g., driver base cost, per-mile cost, profit margin rates) and service capacity/routing protocols (e.g., size of fleet, capacity of vehicles, operational constraints including the number of stops that can be made, route length), based on incomplete information. Then, the protocols of each synthetic bidder are applied to the set of generated demand scenarios to generate synthetic bids. The performance of each synthetic bidder is evaluated based on a predetermined set of KPIs, such as total outsourcing cost, service capability (e.g., parcel delivery time), and so forth. Not limited to simulation tools, one can also leverage MIP/IP-based optimization tools to achieve the same goal, yet in a more aggregate manner.

Once bids are approximated, given the service guarantees for each O-D pair, the orchestrator may draw a distribution of the generated synthetic bids for each logistic activity in terms of service capabilities and discretize the service capabilities into a finite number of potential SLAs. Assigning each a weight as a function of expected cost (e.g., average synthetic bid price) and frequency of each (i.e., number of corresponding synthetic bids), one can model the problem of determining SLAs using integer programming (IP) as an assignment-oriented model that assigns one specific SLA option to each activity such that the O-D service guarantees are met while optimizing the sum of weights. Since the service capabilities at this stage are approximated ones based on incomplete and estimate information and the mathematical model is often a simplification of the real business problem. So, there might be a gap between its solution and reality. Such a model may have left out details that are difficult to quantify and express. Thus, the orchestrator can consider multiple SLA options for logistic activities. To do so, one can consider generating multiple solutions including optimal, near-optimal solutions for the proposed IP model, encoding resulting solutions into mutiple SLA options for logistic activites.

### *2.2.2 Phase 2: Bid Construction*

After the orchestrator has defined the set of bids, bid requirements, and SLAs for each logistic activity, these are commnuicated to the bidders. In Phase 2, each participating bidder tries to address three problems: (1) deciding which logistic activities (service contracts) to bid on (i.e., the most valuable activity bundles), (2) what service capability to offer (i.e., which SLA to bid on), and (3) deciding the bid price for each bundle. When bidders determine the set of profitable logistic activities to bid on, they attempt to make full use of their capacity to decrease overall costs, with different activities having different costs. We differentiate two contexts in which bidders provide logistic services: (i) bidders provide dedicated services (e.g., sub-fleets) assigned to individual clients (e.g., dedicated fleet services for the orchestrator) and (ii) bidders already have pre-existing commitments to other contracts prior to the auction so new logistic activities have to be integrated into a bidder's current operations. In the absence of considering pre-existing commitments, bidders just need to deliberate over their bidding plans based on combinatorial opportunities among new logistic activities. However, in the presence of pre-existing commitments, bidders not only need to consider the combinatorial opportunities among new logistic activities but also need to optimize how these new activities can fit into their current operations while still protecting the pre-existing commitments, which requires making more complicated decisions. In addition to considering the existence of pre-contracted services, bidders must also consider economies of scope when determining which logistic activities to bid on. When cluster transport service bidders decide which cluster activities to bid on, their economics are not solely based on the volume of one-way demand in a cluster. They must optimize the utilization of their resources and balance their needs for equipment and drivers.

An important factor contributing to a cluster transport service bidder's transportation costs (and therefore bid prices) is associated with empty vehicle repositioning. Hub processing service bidders should also consider economies of scope in determining which hub activities to bid on. To exploit economies of scope, hub service bidders can consider relocating resources such as labor, modular capacity over time between a set of hubs to adapt to dynamic demand more efficiently (Faugere and Montreuil, 2017; Faugere et al., 2020).

The set of logistic activities a bidder participating in the auction ends up serving is uncertain due to the participation of other bidders (e.g., competitors) in the auction. The probability that a bidder wins a certain logistic activity/set of activities depends on the bidder’s bid, competitor’s bids, and the SLA that will be imposed on the activity(ies). That is, each bidder should take several factors into account: (1) SLAs imposed on the logistic activities that they are to bid on, (2) type of auction mechanism employed such as first-price auction or second-price auction, (3) the bidder's own cost structure, and (4) the competitor's bidding strategies.

To determine bids, bidders first need to consider modeling their operations for logistic activities that they are to bid on. Cluster transport bidders may use a VRP model to evaluate their capability in their desired activities. Hub processing bidders may develop a sort plan design/cross-docking assignment model. In addition to modelling operations, bidders also need to incorporate modelling game-theoretic decisions in their bid construction. In case of multiple SLAs offered for logistic activities, bidders need to consider which SLA will eventually be selected for their desired logistic activities by the orchestrator in Phase 3 in order to decide on which SLA(s) to select and how much bid price to ask. The bidder's bid price must be high enough to make serving the logistic activities profitable, but low enough to beat competitor's prices. In practice, it is very difficult, indeed almost impossible for bidders to access competitor's strategies. One way to incorporate the competitor's strategies is to consider lowest price offered for logistic activities previously offered (Kuyzu et al., 2015; Yan et al., 2018).

### 2.2.3 Phase 3: Bid Assignment and Service Network Optimization

Once each bidder forms their bids with associated bid prices, these are submitted to the orchestrator. In Phase 3, the orchestrator determines the winning bid among the bids submitted by all bidders (and the selected SLA in case of multiple SLA options) for each logistic activity in a way that minimizes the total outsourcing cost, as illustrated in Figure 6. The orchestrator models this winning bid determination problem using integer programming as an assignment-style model, where one specific bid is assigned to each logistic activity such that the service guarantee of each O-D pair is guaranteed in a cost minimization manner. This indicates the final assignment of SLAs to logistic activities, and bidders to logistic activities, and results in contracts for the termed horizon.

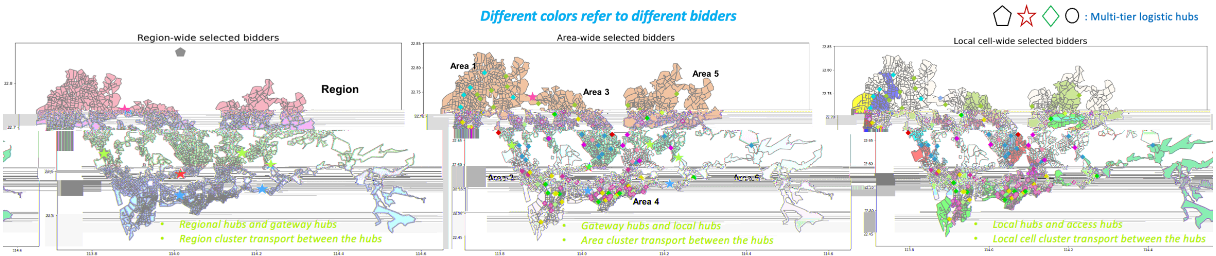


*Figure 6: Example of Output of Phase 3*

In practice, the orchestrator would face uncertain values of parameters such as future demand volume and bidders' service capability/reliability, and it is not always possible to predict or estimate them accurately. Now that the main logistics goals are to deliver the right items to the right place, at the right time under the right conditions, when allocating winning bids to logistic activities, the orchestrator must ensure that the resultant bid-activity assignment leads to robust O-D service guarantees that are stable and less sensitive against possible uncertainties in a cost minimization manner. One common way to consider such robustness is to employ a probabilistic way of handling probabilistic uncertainty aforementioned. For example, the orchestrator may consider an on-time arrival probability of meeting the requirement of the O-D service guarantees. In other words, the orchestrator wants to guarantee the probability (e.g., 99.99% robustness/reliability) such that the robust solution feasibly ensures the O-D service guarantees. One can model this using a chance-constrained model where the probability that O-D service guarantees are met is constraind. The orchestrator will still make sure that the optimal selection of bids leads to planning that are not overly conservative or too costly, which also depends greatly on the SLAs as discussed.

## 3 Conclusion and Future Research Avenues

In this paper, we apply an auction mechanism concept to the design of logistic service networks by outsourcing logistic activities to third-party logistic service providers (3PLs) via a bidding process. We leverage the three-phased combinatorial auction (CA) mechanism that is well-used in the transportation service procurement process, further incorporating it with O-D service guarantees within an urban city and service level agreement (SLA) for each logistic activity. Throughout this paper, we provide the decision-making process of each stakeholder in each phase with modelling ideas that are to be researched and concretized. Introducing the concept of SLAs for logistic activities to the problem adds another dimension of complexity to the decision-making process in each phase, such as considering the reactions of other decision-making stakeholders, and creates another decision perspective view, which makes the proposed problem novel in the context of service network design.

Subsequently, the proposed framework opens future research avenues. Each of the stages in the proposed framework involves optimization and modelling challenges that are related not just limited to the operations of vehicles in clusters and those of hubs, but also to determining SLAs, the reactions of other decision stakeholders, and robustness in the O-D service guarantees. In the combinatorial transportation service procurement auction literature family, the three phases in the proposed framework are often represented as the Shipper Lane Selection Problem (SLSP) for Phase 1, the Bid Construction Problem (BCP) for Phase 2, and Winner Determination Problem (WDP) for Phase 3 (Song, 2023).

When it comes to SLAs, most of the literature on the three problems is only focused on satisfying demand volume (e.g., forecasted volume of packages) and does not address time-aspects of services (e.g, x-hour transport). In addition to time-aspects in the service, most literature considers a single-tier network consisting of a set of origin-destination pairs while we base our framework on the hyperconnected multi-tier mesh networks where parcels move from their origin to destination by traversing multiple planes through multiple logistic activities. This adds another layer of combinatorial complexity. The paper marks key decisions and required capabilities, revealing capability gaps that will be left for future research steps.

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