Hyperconnected Urban Parcel Delivery Network Design with Tight Delivery Service Requirements

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Abstract:

hubs with sorting capability within the urban center close to their customers to better serve them, and sustainable initiatives using electric vans/cargo bikes (CBs) as an alternative to carry last-mile delivery (Winkenbach et al., 2016). Furthermore, inspired by the Physical Internet concept enabling open asset utilization, many are open to change their way of business toward collective actions and cooperative strategies by mutualizing data and resources (Kim et al., 2021). With such multiple delivery actors within an urban city, there still are some remaining challenges: (1) lack of available logistic space to build such micro hubs and (2) congestion of alternative modes of transport including CBs.

In this work, we consider the case of La Poste, French national postal company, that is motivated by the challenges above to redesign their logistic network. La Poste consists of several subsidiaries of parcel delivery actors, each of whom is an independent firm and offers different delivery time service levels (e.g., x-hour delivery) between fixed origin-destination (O-D) pairs in their own dedicated network. Motivated by the case of La Poste and further generalizing it, we study in this work the design of a hyperconnected network for a logistic firm in a similar setting to La Poste where its subsidiary actors are allowed to cooperate and share with others their network components including vehicle resources and micro-hubs to seek tight delivery service requirements in a sustainable manner while maximizing their own profit as a result of their coalitional decisions. We propose a coalitional decision-making framework and shared network design model where both input demands and transportation plan decisions are modelled as a frequency per time (e.g., 1000 parcels per week, 50 cargo bikes per week) in a flat network (not space-time). The proposed framework leverages the network design model to model the coalition-formation decisions of delivery actors to determine whether it is beneficial to stay stand-alone or form a coalition with others, and how to form it.

2 Framework for Hyperconnected Urban Parcel Delivery Network Design

In this section, we present a conceptual framework for the proposed hyperconnected urban parcel delivery network design. We first introduce key decision-making stakeholders involved in designing hyperconnected parcel delivery networks and discuss the main objective and key decisions of each one. Then, we discuss what it means for these stakeholders to form a coalition with others, what is to be cooperated and shared under a formed coalition, and what is to be globally expected from that coalition.

2.1 Problem Description

We consider a coalitional game for the shared network design involving a set of independent parcel delivery actors who are offering a range of parcel delivery services between a predetermined set of its origin-destination pairs (i.e., commodities) in the same geographical urban area. We assume that each of these actors has its own dedicated parcel delivery network and offers a set of service levels (e.g., 6-hour delivery, same-day delivery) in that network. Origins and destinations served by the delivery actors are represented as demand zones which can be thought of as a set of demand points in an urban city where parcels are picked up and dropped off. The parcel delivery network of each actor is structured as a multi-echelon network comprising existing and potential (not opened yet) micro hubs (MHs) within the city that are equipped with sorting capability and distribution centers located in peri-urban areas.

Each commodity is associated with expected revenue and a service level requirement that specifies the maximum amount of time allowed to transfer from its origin to destination. We assume that the delivery network of each actor allows shipments to be transferred between vehicles at intermediate micro hubs. That is, commodities are transported from the origins to destinations via one or more intermediate micro hubs while abiding by actors' operational constraints. Therefore, the main goal of each delivery actor is to optimize its parcel delivery network such that all commodities are feasibly served in a cost-minimization manner. We assume that the overall profit of each actor is defined as the difference in total revenue from serving its demand commodities and total cost incurred to optimize its parcel delivery network. Thus, in order to maximize its profit, each actor must minimize the cost of optimizing its parcel delivery network.

To increase individual's economic benefits, one can consider forming a coalition with other delivery actors. Forming a coalition with other delivery actors means horizontal cooperation. Horizontal cooperation offers the opportunity for actors to access other actors' additional capabilities and capacities and share their own resources with others when underutilized. In this work, we assume that resource sharing includes micro hub sharing and vehicle sharing. Resource sharing is meant to allow other actors to access underutilized resources. As a result of cooperation, micro hubs can share resources such as sorting capability or dock doors and vehicles can be loaded with flows of different actors. For example, suppose we have a vehicle moving from one hub to another and assume that it is 70% full. Then, we may allow other actors who are interested in sending flows in the same direction to access the underutilized vehicle by filling the remaining 30% with flows of other interested actors.

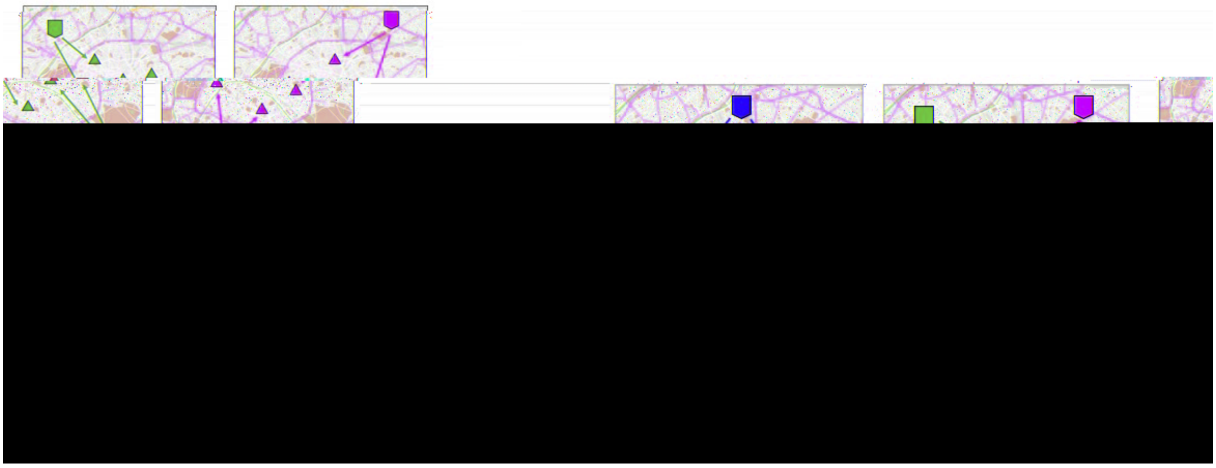

Figure 1: Example of Coalition-Formation of Multiple Parcel Delivery Actors

It is clear that some actors could gain benefits from forming coalitions, yet this opportunity still must be investigated. To do so, several questions must be addressed: Can the actors improve their individual economic performance when they coalesce with others? If so, what is the best coalition for each actor to form so that the profit of each cooperating actor is increased? Even if the global economic performance of a given coalition is larger than the sum of the individual economic performance of actors in that coalition when they stand alone, actors would not form the coalition if their cooperative individual performance is smaller than their stand-alone individual performance. Also, it needs to be addressed how the actors will react to cooperation according to the cost sharing method proposed.

2.2 Coalitional Decision-Making Framework

We propose a coalitional decision-making framework for the proposed hyperconnected urban delivery network design. The proposed conceptual framework shown in Figure 2 takes as input the dedicated parcel delivery network of each actor and consists of two interrelated steps: coalition-formation and shared network design model. We model the problem as a coalition-formation game where the shared network design model is proposed to evaluate the payoff of each possible coalition. The payoffs obtained from the network design model are used to determine the solution of the coalitional game in terms of stable coalition structure (i.e., a set of stable shared parcel delivery networks).

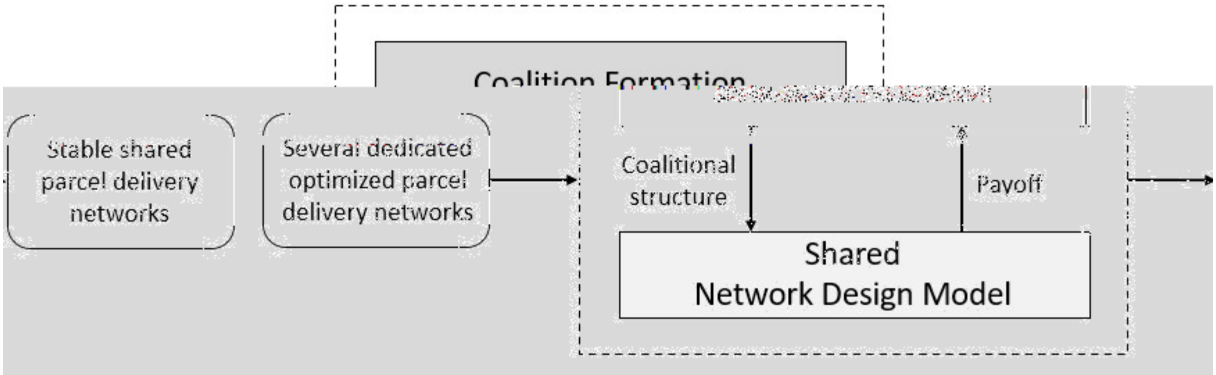

Figure 2: Coalitional Decision-Making Framework

We address (1) which profitable coalition each actor should form, (2) how the shared network of each coalition should be designed to offer timely delivery of each actor in that coalition, and (3) how the joint costs of the shared network should be allocated between actors. To answer (1) and (3), we model the coalitional game of the problem in the stand-alone scenario as a benchmark where actors do not interconnect with each other, and shared scenarios where actors are allowed to interconnect. Actors possibly refrain from coalescing with others when such a coalition does not improve their individual economic performance, regardless of the benefit that the coalition might provide the global system. Thus, the coalitions formed should be desirable from both the global coalition level as well as the local actor level. We use principles from cooperative game theory to identify the most profitable coalitions and to determine the portion of cost that would be allocated to each actor to guarantee the stability of the formed coalitions. We employ different cost-allocation methods such as Shapley's value as different cost-allocation mechanisms could lead to different outputs for the actors (Basso et al. 2020).

2.2.1 Shared-Network Design Model

In this section, we introduce the shared urban parcel delivery network design problem for a coalition of actors. We consider a strategic hub selection problem within the context of service network design. Note that all possible coalitions include a single-actor coalition (i.e., stand-alone case) and thus the proposed model can be used to evaluate the payoff of a stand-alone parcel delivery network. We formulate the shared network design problem as a path-based mixed integer programming (MIP) and frequency-based model on a flat network incorporating time aspects of parcel delivery. In flat networks, demands are modeled as average demand rates per time for each origin-destination pair. The proposed model takes demand rates as input. The goal of the proposed model is threefold: (1) choosing the hubs that encourage consolidation opportunities the most, (2) selecting a joint set of time-feasible paths for all commodities, and (3) along with the paths, allocating required number of vehicles to be dispatched between facilities per time (i.e., vehicle dispatch frequencies) to guarantee the desired timely service levels for O-D pairs in a cost minimization manner. For each commodity, we express its dwell time at intermediate hubs along its (potentially) assigned path using vehicle dispatch frequency variables and link it with its corresponding service level.

For a given coalition s, which can be a subset of actors or single actor, let $(\mathcal{N}^s, \mathcal{A}^s)$ define the coalition's network. The node set $\mathcal{N}^s$ denotes the set of existing and potential locations in the network; these include the set of demand zones that originate shipments, $\mathcal{N}_O^s \subseteq \mathcal{N}^s$, the set of those that are destination demand zones for commodity shipments, $\mathcal{N}_D^s \subseteq \mathcal{N}^s$, , and the set of potential and existing micro hubs where shipments can be sorted and consolidated, $\mathcal{N}_I^s \subseteq \mathcal{N}^s$. Furthermore, each hub $i \in \mathcal{N}_I^s$ has an associated opening cost g_i and specifies an associated lower and upper bound $Q_i^{\min}$ and $Q_i^{\max}$ on the throughput capacity when opened/activated (i.e., minimum and maximum number of vehicle dispatches required). The directed arc set $\mathcal{A}^s$ consists of the set of potential transportation legs linking pairs of locations. Each arc $a \in \mathcal{A}^s$ has an associated travel time t_a and a per-vehicle dispatch arc cost c_a corresponding to a vehicle movement of capacity v. We define $\delta^+(i)$ and $\delta^-(i)$ as a set of incoming/outgoing arcs to/from hub $\mathcal{N}_I^s$.

Origin-destination demand is modeled as a set $\mathcal{K}^s$of commodities. Each commodity $k \in \mathcal{K}^s$ has an associated origin $o_k \in \mathcal{N}_O^s$ and destination $d_k \in \mathcal{N}_D^s$, demand volume rate q_k representing aggregated average shipment quantity from o_k to d_k per time unit (e.g., 1000 parcels per day), expected revenues, and service level $\tau_k$in terms of delivery time requirement from o_k to d_k (e.g., 6-hour, same-day, two-day deliveries). Let $\mathcal{P}_k$ denote the set of potential paths for commodity k, where each potential path consists of a set of pair of locations connecting origin o_k and destination d_k. Thus, for each commodity k, a unique path out of the set must be selected. As the problem is more of a strategic nature, we assume that any fluctuating demand do not significantly affect the feasibility of the consolidation plan. Moreover, although shipments for each commodity k, can be sent from its origin to destination through different hubs over time in practice (i.e., taking different paths over time), we assume that such shipments follow the same path defined by the chosen consolidation plan.

We hereafter introduce a base optimization model for the shared urban parcel network design problem. We define for each $i \in \mathcal{N}_I^s$ binary variables x_i to indicate whether hub i is opened/activated and integer variables y_a to represent the integer dispatch frequency of vehicles on arc per time unit $a, \forall a \in \mathcal{A}^s$ (a dispatch frequency of 10 is interpreted as 10 vehicle dispatches per time unit i.e., 100 vehicle dispatches per week). Let binary variables z_p^k indicate whether commodity k uses path $p, \forall p \in \mathcal{P}_k$. As each commodity has an associated service level (i.e., delivery time requirements), each potential commodity path must be time feasible. That is, the shipment lead time along each commodity path must satisfy the service level. To capture such time aspects in our proposed frequency-based model, we assume that each commodity $k \in \mathcal{K}^s$ arrives at o_k and all vehicles are to be dispatched between locations according to a uniform distribution. We then use a similar approach in the work by Greening et al., (2022) and Dayarian et al., (2022) for network design problems to handle the time requirements of commodities in a frequency-based model. We suppose that the shipment lead time of commodities is determined by the arcs and intermediate hubs along each route. The times spent traversing the arcs and hubs along each path include travel time across arcs, handling time, and dwell time at each intermediate hubs along the path. Therefore, a potential path for each commodity k is said to be time-feasible if and only if the sum of travel times of all arcs along the path, the handling times at all its intermediate hubs, and expected dwell times at the hubs along the path does not exceed the service level, τ_k In other words, for each commodity $k \in \mathcal{K}^s$ and each path $p \in \mathcal{P}_k$, the following must be satisfied:

$$\sum_{a \in p} t_a + \sum_{i \in p \setminus \{o_k, d_k\}} h_i + \sum_{i \in p \setminus d_k} \mathbb{E}\left[w_{ip}\right] \leq \tau_k$$

$$\rightarrow \sum_{i \in p \setminus d_k} \mathbb{E}\left[w_{ip}\right] \leq \widehat{w}_p^k = \tau_k - \sum_{a \in p} t_a - \sum_{i \in p \setminus \{o_k, d_k\}} h_i \qquad (1)$$

, where h_i denotes fixed handling time at hub i independent of commodity flow, and $\mathbb{E}[w_{ip}]$ denotes the expected dwell time at intermediate hub $i \in p \setminus \{o_k, d_k\}$, and $\widehat{w}_p^k$ denotes the maximum allowable dwell time along path p for commodity k. Expected dwell time at hub i along path p depends on the outbound dispatch frequencies along the arc leaving hub i along path p. We assume that given the vehicle dispatch frequency y_a on arc a, vehicles are dispatched every $\frac{1}{y_a}$ time units. With the uniform distribution assumption, the expected dwell time at intermediate hub i along path p can be modeled as $\mathbb{E}[w_{ip}] = \frac{1}{2} \cdot \frac{1}{y_a}$. We can formulate this model as follows:

$$\min \sum_{i \in \mathcal{N}_I^s} g_i \cdot x_i + \sum_{a \in \mathcal{A}^s} c_a \cdot y_a \qquad (2)$$

$$\sum_{p \in \mathcal{P}_k} z_p^k = 1, \qquad \forall\, k \in \mathcal{K}^s \qquad (3)$$

$$\sum_{k \in \mathcal{K}^s} \sum_{\{p \in \mathcal{P}_k : a \in p\}} q_k \cdot z_p^k \leq v \cdot y_a, \qquad \forall\, a \in \mathcal{A}^s \qquad (4)$$

$$\sum_{a \in p} \frac{1}{2} \cdot \frac{1}{y_a} \leq \widehat{w}_p^k + M \cdot \left(1 - z_p^k\right), \qquad \forall\, k \in \mathcal{K}^s, p \in \mathcal{P}_k \qquad (5)$$

$$\sum_{a \in \delta^-(i)} y_a \leq Q_i^{max} \cdot x_i\,, \qquad \forall\, i \in \mathcal{N}_I^s \qquad (6)$$

$$\sum_{a \in \delta^-(i)} y_a \geq Q_i^{min} \cdot x_i\,, \qquad \forall\, i \in \mathcal{N}_I^s \qquad (7)$$

$$\sum_{a \in \delta^+(i)} y_a \leq Q_i^{max} \cdot x_i\,, \qquad \forall\, i \in \mathcal{N}_I^s \qquad (8)$$

$$\sum_{a \in \delta^+(i)} y_a \geq Q_i^{min} \cdot x_i\,, \qquad \forall\, i \in \mathcal{N}_I^s \qquad (9)$$

$$\mathbb{x}, \mathbb{z} \in \{0,1\} \qquad (10)$$

$$\mathbb{y} \in \{0,1\} \qquad (11)$$

The objective function (2) minimizes the total cost including micro hub opening cost and variable costs incurred along the operated arcs. Constraints (3) ensure that one path per commodity is selected. Constraints (4) allow flow along each arc only if there is vehicle dispatch and enforce an aggregated vehicle dispatch capacity. Constraints (5) assure that enough vehicle dispatch frequency must be allocated along each arc of the chosen path for each commodity so that the maximum allowable dwell time along the path is not violated. Constraints (6)- (9) set required vehicle dispatch frequency for each hub opened. To avoid such nonlinearity in Constraints (5) we propose two linearization approaches along with the model: (1) allocating the maximum allowable dwell time equally among the arcs of each path and (2) introducing a discretization of the domains of vehicle dispatch frequencies along each arc as proposed by Cancela et al., (2015).

2.2.2 Cost-Allocation Methods

As mentioned before, whether an actor wants to coalesce with others depends on how much benefit they receive from forming a coalition with others compared to the case where they stand alone. Actors would want to form a coalition with others if the cost allocated to them in the shared scenarios is less than or equal to the cost allocated to them in the stand-alone scenario. In other words, the cost-allocation method impacts the decision of actors to form coalitions. An essential requirement is that the resulting allocations satisfy the individual rationality condition for all actors, that is, the profit obtained from forming coalitions exceeds the individual profit. Note that different cooperative game solution concepts for allocating joint costs as different sharing mechanisms could lead to different outputs for the actors (Basso et al. 2020). We here focus on three most well-known cost allocation mechanisms: Shapley value, Proportional allocation (PA), and Egalitarian allocation (EA) which are among the most used cost allocation mechanisms in the literature on collaborative transportation (Guajardo et al., 2015). We refer to the work of Jouida et al. (2021) for the definition of each cost-allocation method above.

3 Preliminary Experiments

To test the modelling and understand the impact of coalitional decisions of actors, we apply the developed framework, optimization model, and three cost-allocation methods to a large-scale urban network instance of the La Poste group for case study. We show how the proposed framework can be leveraged to evaluate network's service capability of each actor such as at what cost their desired service level goals can be reached in stand-alone and shared scenarios, respectively. We consider 3 delivery actors, subsidiaries of the La Poste Group, serving an urban city with 412 demand zones expecting a weekly demand on the order of 1.6 million parcels weekly across 52,000 origin-destination (O-D) pairs. We consider each delivery actor offers 3 different service levels and the weekly demand for each actor is derived according to their historical market share for the given urban city. We assume that all the micro-hubs of actors are homogeneous in terms of capacity/size. Tables 1 and 2 summarize the network and demand information of delivery actors and possible coalitions, respectively. Default values for parameters used in the model are set according to the historical practice of La Poste.

Table 1: Summary of Delivery Actors

Delivery Actor	No. Micro-hubs	Market Share	No. O-D Commodities
1	25	60%	35591
2	3	10%	6162
3	8	30%	18105

Table 2: Summary of Possible Coalitions

Coalition	No. Micro-hubs	No. O-D Commodities	Description
(1,)	25	35591	Standalone
(2,)	3	6162	Standalone
(3,)	8	18105	Standalone
(1,2)	28	41301	Coalition of Actors 1 and 2
(1,3)	33	52472	Coalition of Actors 1 and 3
(2,3)	11	24044	Coalition of Actors 2 and 3
(1,2,3)	36	57968	Grand Coalition

The aim of this preliminary experiment is to understand the impact of coalitional decisions of actors on the global network design performances and the impact of the cost-allocation methods on the coalitional decisions of actors. For the global network design performance indicators, we consider the total overall network design cost and overall usage of transportation resources in terms of number of dispatches for each possible coalitional structure. For the coalition performance indicators, we consider the number of cooperative actors, number of profitable coalitions, and cardinality of the optimal coalition structure for each cost-allocation method (denoted respectively with No. Cop. Acts, No. Prof. Coal, and |Coal| in Table 3).

Figure 3 reports the global network design cost and total resource usage in terms of number of vehicle dispatches per possible coalitional structure. As shown in Figure 3, forming coalitions leads to the reduction in the overall network design cost and number of dispataches, and the best performance is achieved when the grand coalition is formed, that is, when all actors belong to the same coalition. However, coalitions can only happen when the rationality condition holds for all actors. That is, the actors will coalesce only when the overall profit achieved from forming coalitions exceeds the individual profit from working standalone, which depends on how the joint costs are allocated.

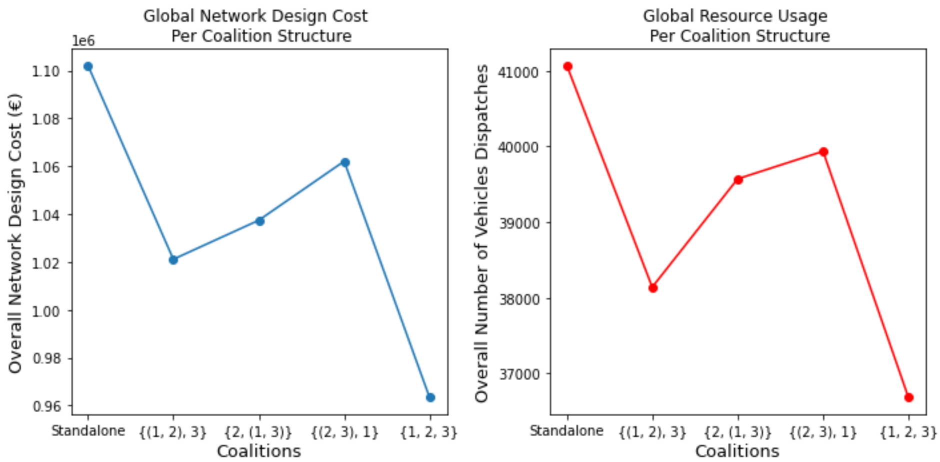

Figure 3: Global Network Design Performance

Table 3 reveals that the Shapley allocation and PA methods lead to the formation of more coalitions than the EA method. For the EA method, all the actors prefer to work standalone as joining coalitions is not beneficial to them while the Shapley and PA methods lead to all actors willing to coalesce. The cardinality of the optimal coalition structure indicates that the actors are willing to form a grand coalition. Detailed results of the impact of cost-allocation methods on all actors are shown in Figure 4. This phenomenon can be explained by the characteristics of the instance considered in the preliminary experiment. The market shares of the actors are not well-balanced; actor 1's market share is dominating the others. In this case, The EA method which does not account for marginal contribution of actors would be significantly beneficial to the dominating actor while it would be detrimental to the other actors, leading to them wanting to work standalone. Different instances with different market shares among actors and parameters will lead to different coalitional structures. These results still underline that the cost-allocation method incentivizes the actors' decision to coalesce.

Table 3: Summary of Coalitional Decisions per Cost Sharing Method

Tot. No. Coal	Shapley			Proportional (PA)			Egalitarian (EA)		
	No. Cop. Acts	No. Prof. Coal	|Coal|	No. Cop. Acts	No. Prof. Coal	|Coal|	No. Cop. Acts	No. Prof. Coal	|Coal|
7	3	5	1	3	5	1	0	0	3

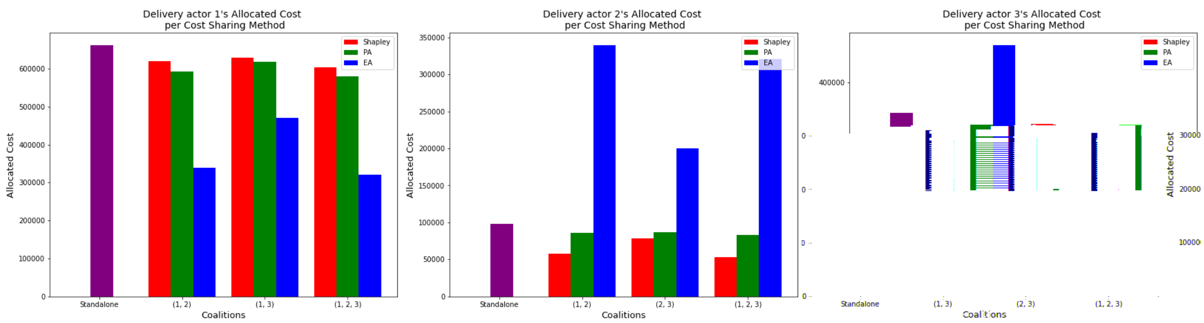

Figure 4: Allocated cost to actors per cost-allocation method

4 Conclusion and Future Research Avenues

The network design problem studied in this paper considers designing a cooperative parcel delivery network in which multiple actors coalesce to efficiently serve a number of transport demands and maximize their profit. Cooperation is viewed as a concept aiming to pool resources by seeking better resource utilization through smart consolidation to maximize one's profit. In this paper, we motivate the resource-sharing concept in the realm of the Physical Internet initiatives in the context of the urban parcel delivery network deisgn. Furthermore, we leverage a cooperative framework to model the problem as a coalition formation game. The preliminary experimental study highlights the importance of horizontal cooperation in the pursuit of actors' profit growth and sustainability. It also observes that forming coalitions depends on the cost allocation method used. Indeed, using various cost sharing methods, we observed that different methods can lead to different coalitions.

Future research steps could include adding more dimensions such as problem size, network configuration, different hub sizes, different cost structure to analytically see how the cooperative decision conditions can be derived according to the cost-sharing methods considered. For modelling, this paper assumed that arriving demand and vehicle dispathces between hubs follow a uniform distribution and derived Equation (5) for the delivery service requirements. However, this would imply that the commodity travelling along its path arrives at its destination on time with probabilty of 0.5. Future works could remove this assumption and address robust perspective in the commodity lead-time requirement.

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