Potential Access Hub Network Design Optimization in Hyperconnected Urban Logistics

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Abstract: *In the context of Hyperconnected Logistics Network, access hubs are first-tier consolidation and transshipment points which facilitate direct transfer of parcels between unit zones via couriers. These hubs can foster resiliency by being assigned to multiple unit zones when located at their intersections. In this paper, we propose an optimization based approach leveraging modularity to design a potential access hub network that need not be implemented as designed, but rather fed into large scale network design and clustering optimization models to improve its solvability when accounting for comprehensive inter-hub flow. Then, we study the efficiency and robustness of the proposed model through a set of experiments performed with an illustrative case representative of world's megacity inspired from a large parcel express carriers' operation. Results indicate that we should leverage on the capability of an access hub to serve more unit zones given its capacity restrictions. Finally, we identify promising future avenues for research and innovation enabling Logistics Service Providers (LSPs) in achieving their goals of serving efficiently and sustainably while offering fast and precise delivery services.*

Conference Topic(s): *Ports and hubs in Interconnected freight transport, logistics and supply networks*

Keywords: *Hyperconnected City Logistics, Physical Internet, Omnichannel Supply Chains, LSPs, Large scale hub-location problem*

1 Introduction

With the rise in e-commerce over the last decades, there has been a dramatic global shift in the demand for customer responsiveness. Buying items online has become a simple process which can be done within a matter of minutes at the click of a button. This growth is particularly pronounced during the COVID-19 pandemic, in which logistics firms have been inundated with online orders. For instance, between March and May 2020, when many stores were shuttered, online commerce increased 21% from March 2019 to March 2020, accompanied by a 45% rise in online purchases that used to be in-store purchases. In the view of many analysts, those behavioral changes may be permanent, Gurram et al. (2021). To cater to these changes and remain competitive by serving efficiently and sustainably, logistics service providers (LSP's) are challenged to break away from their conventional methods of operations such as hub-and-spoke networks and point-to-point networks.

In this direction, Montreuil et al. (2018) proposes a transformation towards a logistics topology web based on multi-tier hierarchical space structuring and an interconnected multi-plane logistics mesh networks, applying the concepts of hyperconnectivity underpinning the Physical Internet. This transformation is exacerbated in megacities which are the focus of this paper. At the first tier, megacities are represented as a mesh of unit zones constituting a demand area, such as a neighborhood, a city block, a university campus, an industrial park, a high-rise building, or a set of stories of high-rise building, clustering the pickup and delivery locations into courier work zones as shown in Figure 1, Montreuil et al. (2018). Each of the unit zones is a relatively small geographical area and can be defined as an intricate polytope except for high rise buildings, where we must specify height as well.

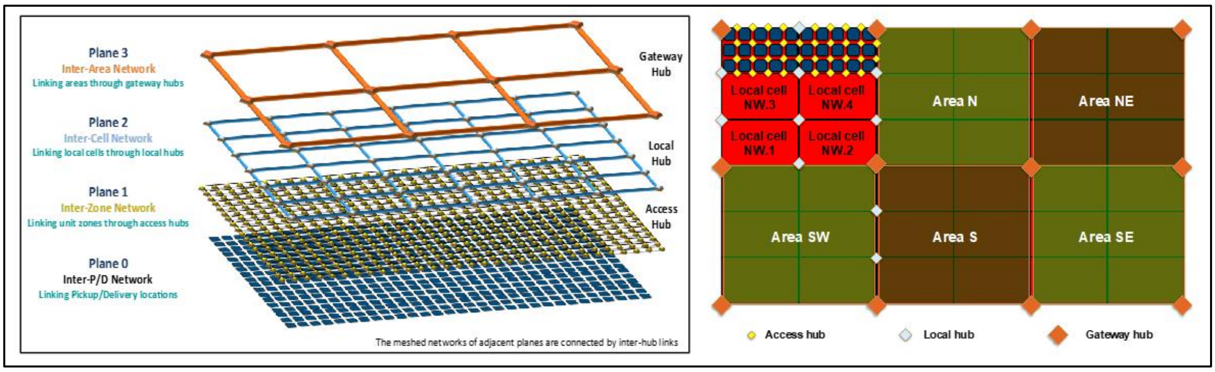

Figure 1: Urban Parcel Logistics Web Topology, Montreuil et al. (2018)

Access hubs are first-tier consolidation and transshipment points which facilitate direct transfer of parcels between unit zones via couriers and these hubs can foster resiliency by being assigned to multiple unit zones when located at their intersections. Due to urban infrastructure, a vast number of sites can be identified for the role of access hub in the neighborhood of each unit zone. Filtering out potential locations among this huge set considering the courier travel, real-estate availabilities and local government regulations is a key decision process for LSPs so that their optimization efforts taken towards overall urban logistic network design and urban space clustering remains tractable when dealing with large scale cities.

This paper proposes an optimization based approach for designing a potential access hub network in the presence of large set of candidate locations. Such potential access hub networks do not aim to be implemented as designed, but rather to be the input to a comprehensive urban logistic design process. In the case of a stationary access hub network, it provides candidate set of access hub locations that is of a scale amenable to optimization accounting for comprehensive inter-hub flow modelling. In the case of a mobile hub network, it provides the set of locations from which are to be selected the actual locations where mobile hubs will be dynamically located through the day (or week) depending on demand fluctuations, through the optimization framework proposed in Faugère et al. (2020). Potential access hub network design purposefully makes simplifying assumptions to enable optimization in a very large scale context. The proposed optimization modelling approach accounts approximately for pickup and delivery demand stochasticity, service level requirements and hub capacity. Given these considerations, the proposed model optimizes hub-zone covering given targets relative to the maximum number of unit zones that an access hub may serve, and the number of access hubs serving each zone.

Section 2 summarizes the advances in literature regarding the large-scale hub location allocation problems. Section 3 describes the problem studied and the proposed framework in detail. Section 4 presents the set of experiments performed with an illustrative case representative of a megacity inspired from a large parcel express carrier’s operation. Section 5 underscores the key takeaways and guidelines for the researchers and managers and identifies promising avenues for future research and innovation.

2 Related Work

Hub location allocation problems have garnered a lot of attention from researchers over the past few decades. A comprehensive review of key developments related to this problem can be found in Campbell et al. (2012). It has applications in several areas but for the context of this paper, we study its evolution in addressing challenges faced by the freight transportation industry particularly parcel-delivery networks.

In most of the previous literature, hubs are referred to facilities that serve as switching, transshipment, and sorting points where most of the traffic are routed to tap into economies of scale (Alumur et al., 2008). Hub location allocation problems are concerned with deciding on the number, location, and size of these points along with its allocation to demand nodes. There are essentially two types of basic networks – single allocation and multiple allocation. In single allocation network, all traffic related to a demand node is routed through single hub while in multiple allocation, demand nodes can receive and send parcels through multiple hubs.

The first acknowledged mathematical formulation of hub allocation location problem started with the seminal work of (O'Kelly et al.,1986; O'Kelly et al., 1987). He introduces a quadratic programming model for uncapacitated *p*-hub location single allocation problem by studying airline passenger networks, where *p* uncapacitated hubs have to be located to exchange traffic among *n* nodes. Campbell (1994) presents an integer programming formulation for discrete hub location problems. Following this, Ernst et al. (1999) considers a capacitated single allocation hub location problem motivated by a postal delivery application and proposed simulating annealing to obtain good upper bounds that are used in a branch-and-bound algorithm. Bruns et al. (2000) discusses restructuring of Swiss Postal Services as a simple allocation location problem with more emphasis on determining the cost parameters of the model. Generally, in classical capacitated hub location problem, the flow that can be received by the hubs i.e.) capacity of hubs are limited. da Graca Costa et al. (2008) presents two alternative bi-criteria single allocation models that tries to minimize the time to process the flow entering the hubs rather than limiting the capacity of the hubs.

Several studies have been conducted in multiple allocation hub location problem as well. Aykin (1993) studied a capacitated hub-and-spoke design problem under a non-restrictive policy allowing two-stop services. Ebery et al. (2000) considers a capacitated multiple hub location problem and presents a mixed integer linear programming formulation along with an heuristic algorithm using shortest paths. Determining the locations of hubs and allocation of non-hub nodes simulataneously, complicates the development of solution techniques for these problems.

de Camargo et al. (2008) presents a Benders decomposition algorithm based on a well known formulation to tackle the uncapacitated multiple allocation hub location problem. They were successful in solving large scale instances in reasonable time which were considered to be out of reach of other contemporary exact methods. The emergence of global supply chains has led to the sustained demand for intermodal transportation. Design of transportation network for intermodal logistics is more complex compared to single mode logistics. Arnold et al. (2002) formulated a linear 0-1 program and applied it to a rail/road transportation system in the Iberian Peninsula. It shows that the modal shares of the goods which have their origin or their destination in Iberia is very sensitive to the variation of the relative cost of rail. Ishfaq et al. (2011) develops a mathematical model using multiple-allocation *p*-hub median approach that encompasses the dynamics of individual modes through transportation, modal connectivity, and fixed location cost structures.

These models are driven by the hub-and-spoke network topology, based on single-level view of hub as consolidation and sortation centers. Montreuil (2011) asserts that the way physical objects are transported, handled, stored through these networks are unsustainable economically, environmentally and socially. He introduces a new paradigm called The Physical Internet (PI,

π) as a response to what he termed the *Global Logistics Sustainability Grand Challenge,* where the movement of freight proceed in a consolidated way through a series of carrier services and relay facilities. Crainic et al. (2016) adds to this by exploring the necessary links and synergy between Physical Internet and City Logistics and introduces the notion of Hyperconnected Logistics along with nine fundamental concepts offering a rich framework for designing sustainbale urban logistics. Montreuil et al. (2018) used Physical Internet's hyperconnectivity and modularity conceptual pillars to develop a logistic topology web based on multi-tier hierarchical space structuring and an interconnected multi-plane logistics mesh networks enabling future generation of parcel logistics hubs to be capable of supporting X-hours (ultimately X-mins) delivery services. Access hubs are transshipment and consolidation points located at the neighborhood level and can be allocated to single or multiple demand centers termed as unit zones.

Transition towards Hyperconnected Urban Logistics requires restructuring of the overall urban logistic network design and urban space clustering. This paper fills the gap in literature by proposing an optimization modelling framework that allows multiple allocation of hubs to unit zones to generate the potential set of access hub locations which can be fed to large scale network design optimization models to make it solvable in appropriate time given its more in-depth modelling. Furthermore, with the advent of more sustainable solutions to urban logistics challenge such as mobile access hubs, it provides a solid base to filter the overall possible location set to be fed into more evolved planning models like the one proposed in Faugère et al. (2020).

3 Problem Description and Methodology

3.1 Problem Description

A large parcel express company provides pickup and delivery services to customers residing in an urban agglomeration such as a megacity. This territory is divided into a set of unit zones constituting a demand area whose borders are drawn by the transportation infrastructure (e.g., streets, boulevards) and geographic constraints (e.g., coast, hills, parks, and lakes). Each unit zone is assigned with a courier, typically one who is proficient about its geography and customer base. These couriers are responsible for transshipment of parcels between his respective unit zone and the access hub(s) at its neighborhood. Due to the urban infrastructure, a vast number of sites can be identified for the role of access hubs in the neighborhood of each unit zone. The objective of the company is to design a potential access hub network from a large set of candidate locations using gross approximations of the local hubs in a priori estimations of costs so that it can enable network design and clustering optimization models to remain tractable in time while accounting for comprehensive inter-hub flow which in turn can meet specific service level targets. In the context of this paper, the following assumptions are made:

- Each unit zone can be assigned to multiple access hubs and each access hub can be assigned to multiple unit zones.
- Operations are planned to serve the entire demand of the megacity.
- Capacity at access hubs is adjusted by adding modules of fixed capacity and there is a fixed cost associated with adding a module.
- Deployment of hub at a location has an associated geo-specific cost which can be interpreted as land reservation costs and is independent of number of modules.
- Percentage imbalances in demand flow assignments to hubs is known for each unit zone.
- Rider cycle times to each unit zone is given.

3.2 Methodology

3.2.1 Allocation of locations to unit zones

Before solving the optimization model, we must establish the relationship between the unit zones and access hub candidate locations i.e.) for each access hub candidate we must determine the set of unit zones it can serve. Owing to the considerations in access hub capacity along with the goal of reducing cost of couriers incurred in traversing to unit zones to meet service level requirements, an access hub is confined to serving their immediate neighboring unit zones only. A simple method would be to fix a threshold distance from the candidate and assign it to those unit zones which are covered under the imaginary circle drawn with threshold distance as radius. However, practically speaking, an urban agglomeration such as a megacity consists of a diversity of unit zone shapes and sizes depending on what it represents. Hence, it is not surprising to see regions with dense collection of unit zones smaller in area (e.g., cluster of high-rise buildings) and regions with sparse collection of larger unit zones as depicted in Figure 2. Having a fixed threshold for all candidate locations in a megacity fails to account for diversity in unit zone shapes, sizes, and demand profile. This calls for a geo-specific threshold that accounts for demand density of unit zones in the neighborhood of each candidate location. Then by using the corresponding geo-specific threshold for each candidate location, we can determine the set of unit zones it is capable of serving given the considerations on hub capacity and service level requirements. Further, for each zone, we can determine the set of candidate locations capable of serving it.

For example, as shown in Figure 2, if we assume same threshold radius of $'R'$ from location shown in sky blue in both denser and sparser regions, then a hub deployed in that location would be capable of serving 18 unit zones in denser region compared to 7 unit zones in sparser region which might not be beneficial in terms of meeting hub capacity and service level requirements. However, if we assume a threshold radius of $'r'$ for the dense region indicated by yellow circle in Figure 2(a), a hub deployed at that location would be capable of serving 7 unit zones only as expected.

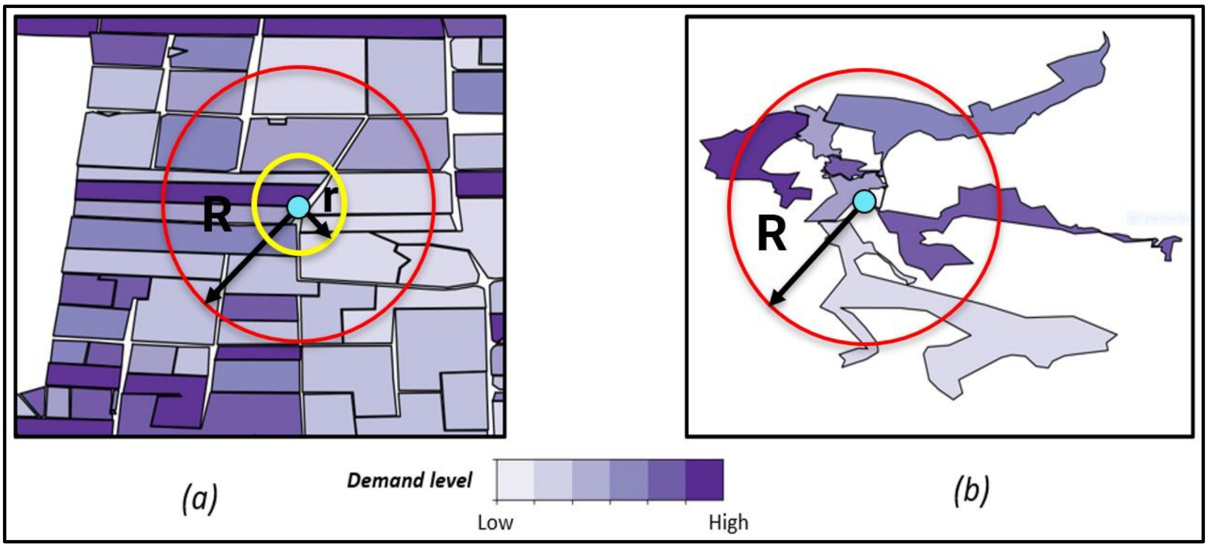

Figure 2: (a) Dense collection of unit zones smaller in area (b) Sparse collection of unit zones larger in area

3.2.2 Pickup and Delivery Routes

The starting point of the proposed modeling is the approximation of the vehicle routing problem via the route length estimation proposed by Daganzo (1984) and exploited in Faugère (2020). In case of couriers performing *s* stops in unit zone *u* from a hub, say *h*, the total distance travelled can be expressed as the combination of stem distance (from the originating hub to the area of service) and an in-tour distance (in the area of service) as follows:

$$D_u(s_u, h) = 2d_{hu}\frac{s_u}{Q_u^h} + s_u k(\delta_u)^{-\frac{1}{2}} \tag{1}$$

where d_{hu} is the average distance between the originating hub h and unit zone u, s_u is the number of stops to perform in unit zone u,Q_u^h is the length or routes of couriers operating in unit zone u from hub h and δ_u is the density of customer locations in unit zone u. k is a constant related to the distance metric used that can be computed by simulation, Daganzo (2005). Similarly, the total time required to perform courier routes can be expressed as follows:

$$T_u(s_u, h) = \frac{s_u}{Q_u^h}\left(t_{fixed}^{courier} + \frac{2d_{hu}}{v_o^{courier}}\right) + s_u\left(\frac{k(\delta_u)^{-\frac{1}{2}}}{v^{courier}} + t_{stop}^{courier}\right) + n_u v t_{handling}^{courier} \tag{2}$$

where $t_{fixed}^{courier}$, $t_{stop}^{courier}$ and $t_{handling}^{courier}$ are respectively the couriers' fixed time for each route, the stopping time at each customer location in the route and handling time per unit, $v_o^{courier}$ and $v^{courier}$ are respectively the couriers' stem and in-tour speed, and the average number of parcels handled per stop. Finally, the induced operations cost can be approximated as follows:

$$C_u(s_u, h) = \frac{s_u}{Q_u^h}\left(c_{fixed}^{courier} + 2d_{hu}c_o^{courier}\right) + s_u k(\delta_u)^{-\frac{1}{2}} c^{courier} + T_u(s_u, h)\, c_{wage}^{courier} \tag{3}$$

where $c_{fixed}^{courier}$, $c_o^{courier}$, $c^{courier}$ and $c_{wage}^{courier}$ are respectively the courier's fixed cost per route, variable cost on the stem part of a route, variable cost in-tour and variable wage per unit of time (e.g., \$/hour).

3.2.3 Mathematical model

Indices:
h candidate location $h \in A$
u unit zone $u \in U$

Mathematical Sets:
U set of unit zones
A set of candidate locations
P set of {unit zone, candidate} pairs where $(u, h) \in$ P implies unit zone $u \in U$ can be served by access hub at location $h \in A$.

Parameters:
s_u total pickup and delivery demand of unit zone $u \in U$
m_u minimum number of hubs to be present at the assumed distance from unit zone $u \in U$
t_h maximum number of unit zones that can be served by hub at location $h \in A$
C_m fixed cost of adding a module
$C_u(s_u, h)$ operation cost estimates of courier (s) serving $u \in U$ from hub at $h \in A$
$C_d(h)$ fixed cost of deploying a hub at location $h \in A$
Q_u maximum of inbound or outbound parcels at unit zone $u \in U$ during rider cycle
α capacity of a module
g_u known % imbalance in demand assigned to hubs capable of serving unit zone $u \in U$, $g_u = 0$ if $m_u = 1$

Decision Variables:
X_h 0-1 variable indicating if hub is deployed at location $h \in A$
Y_{uh} 0-1 variable indicating if hub at location $h \in A$ is chosen to serve $u \in U, \forall\, (u, h) \in P$
Z_h number of modules added at location $h \in A$

Model:

$$\min \ \left(\sum_{(u,h)\in P} C_u(s_u, h) * Y_{uh} + \sum_{h\in A} C_d * X_h + \sum_{h\in A} C_m * Z_h \right) \tag{4}$$

$$s.t. \ \sum_{u\in U} Y_{uh} \le t_h * X_h \qquad \forall \ h \in A \tag{5}$$

$$\sum_{h\in A} Y_{uh} \ge m_u \qquad \forall \ u \in U \tag{6}$$

$$\sum_{u:(u,h)\in P} \left(\frac{1}{m_u} + g_u\right) Q_u * Y_{uh} \le \alpha * Z_h \qquad \forall \, h \in A \tag{7}$$

$$Z_h \le M X_h \qquad \forall \, h \in A \tag{8}$$

$0 \le Y_{uh}, X_h \le 1$ $\qquad X_h, Y_{uh}, Z_h$ *Integers* , M is a sufficiently large positive number

Objective function (4) aims at minimizing the sum of estimated costs induced by courier operations, deployment of hubs at candidate locations and deployment of modules at hubs. Constraint (5) enforces that a hub deployed at location $'h'$ can serve a maximum of t_h unit zones. Constraint (6) ensures that required minimum number of hubs are present at assumed distance from each unit zone $'u'$. Constraint (7) enforces that the number of modules added to hub at location $'h'$ is protected against demand flow imbalances and meet the respective capacity requirements during each rider cycle. Constraint (8) enforces that the modules are added only when a hub is deployed at location $'h'$.

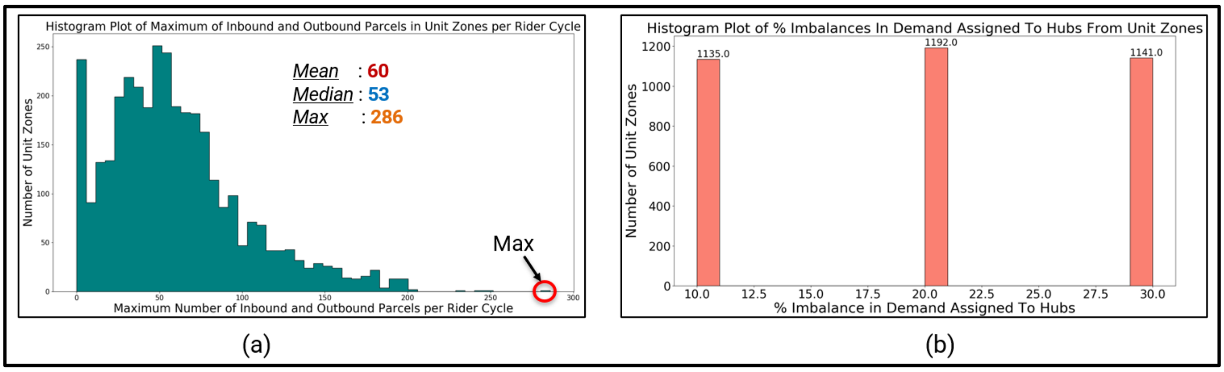

Figure 3: Histogram Plot of (a) Maximum of Inbound and Outbound Demand in Unit Zones per Rider Cycle (b) Percentage Imbalances in Unit Zone Demand Flow Assignments to Hubs for Illustrative Case

4 Results and discussions

In this section, we assess the potential of locations chosen by the model for access hub deployment through a set of experiments performed on an illustrative case inspired from a large parcel express carrier's operation. The experiments were implemented in Python 3.7 using Gurobi 9.0 as the solver and were computed on a laptop with an Intel(R) i7-9750H CPU @ 2.60GHz (Intel, Santa Clara, CA, USA).

The case is representative of a real-world Asian megacity with heterogenous demand profile. It consists of 3,468 unit zones and 52,148 candidate locations for access hub deployments. Figure 4 illustrates the considered megacity's geography and demand profile along with the set of initial candidate sites located either at the centroid or at the intersection of the unit zones. Demand averages between 0 to 4,704 parcels per unit zone with a total demand of 1.35 million parcels across the megacity. The rider cycle times are considered to be 2 hours for unit zones with maximum 2-hour inbound and outbound flow lesser than 200 parcels, 1 hour if maximum 2-hour demand is between 200 and 500 parcels and 30 minutes if it is above 500 parcels. Accordingly, maximum of inbound and outbound flow per rider cycle varies from 0 to 286 parcels per unit zone with an average of 60 parcels per unit zone per rider cycle as shown in Figure 3(a).

If the inbound (or) outbound flow of unit zone is split equally among assigned hubs, then it is a case of perfect balance. However, in real-world it is most likely that the flow is not balanced among assigned hubs to meet service level requirements, in which case hub has to be protected against this through additional capacity. Histogram plot of known percentage imbalances in unit zone demand assignments to hubs for the illustrative case is displayed in Figure 3(b), for example there are 1135 unit zones with 10% imbalance in demand assigned to hubs capable of serving them.

As discussed earlier, firstly we must determine the set of unit zones each candidate location is capable of serving. Setting geo-specific threshold distance from each location as min{50m, $\sqrt{Median\ Area\ of\ neighboring\ unit\ zones}$} found to be promising for our experiments. In future work, we can conduct sensitivity analyses to study the impact of different threshold distances on the total cost estimates. Capacity of access hubs are adjusted by adding modules of fixed capacity of 50 parcels (α) and cost of adding each module (C_m) is $50 irrespective of the hub location. Default values for parameters used in the model are listed in Table 1.

Table 1: Default Experiment parameters

Parameter	Value	Description	Parameter	Value	Description
$t_{fixed}^{courier}$	1 min	*Courier fixed time*	$c_o^{courier}$	$0.15/km	*Courier variable cost in stem*
$t_{stop}^{courier}$	0.5 min	*Courier stop time*	$c^{courier}$	$0.1/km	*Courier variable cost in tour*
$t_{handling}^{courier}$	0.05 min	*Courier handling time*	$c_{wage}^{courier}$	$10/h	*Courier hourly rate*
$c_{fixed}^{courier}$	$10/h	*Courier fixed cost*	$v_o^{courier}$	25 km/h	*Courier stem speed*
C_m	$50	*Cost per module*	α	50 parcels	*Capacity per module*
$\bar{Q}$	35	*Courier Capacity*	$v^{courier}$	8 km/h	*Courier in-tour speed*

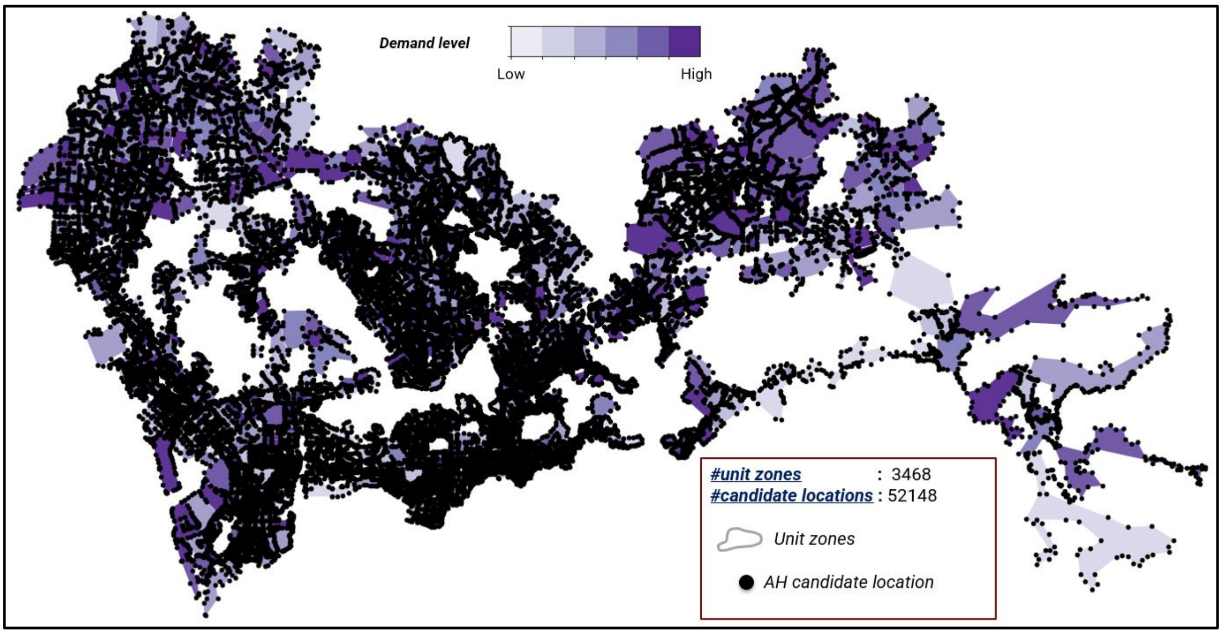

Figure 4: Initial set of candidate locations considered for access hub (AH) deployments

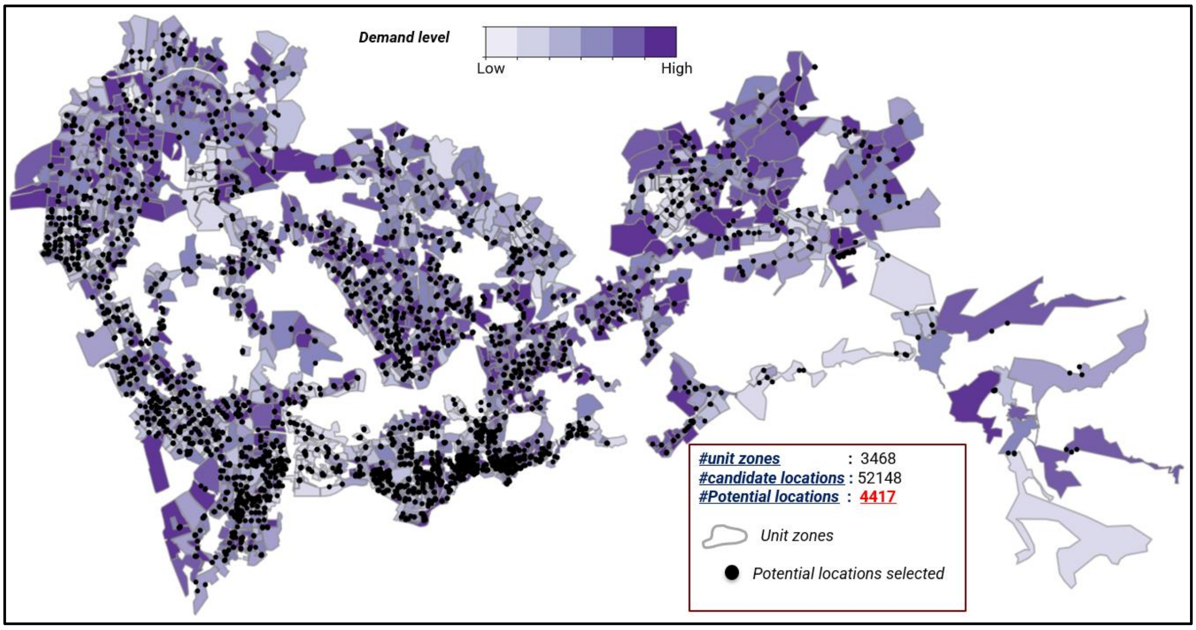

Figure 5: Potential locations selected by the model for the illustrative case with: $m_u = 3$, $t_h = 4$

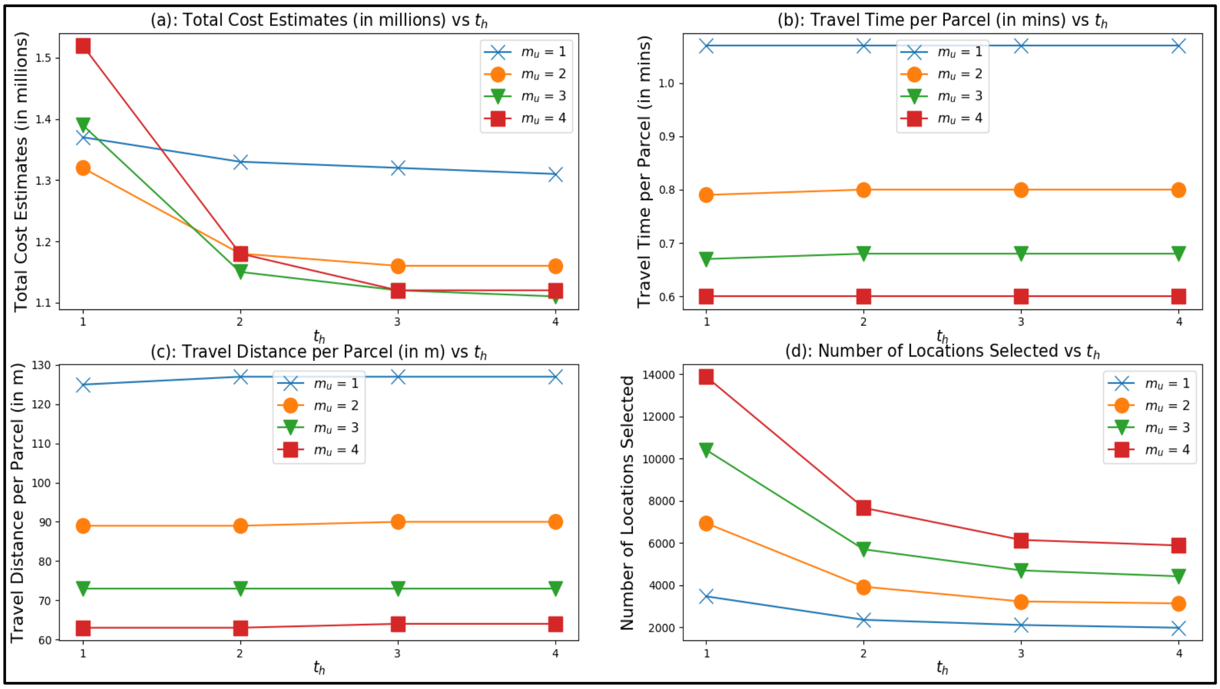

Figure 6: Several Performance Indicators vs t_h for different minimum number of hubs per unit zone (m_u) constraints

Output of the model provides a set of access hub locations to be activated, the set of zones expected to be served by each candidate location, the set of activated access hub locations from which a zone is expected to serve from, and the expected capacity to be deployed at each location to robustly be able to ensure adequate service.

Figure 6 provides the sensitivity analysis of several performance indicators against the maximum number of unit zones an access hub can serve (t_h) while enforcing different values for minimum number of hubs required near each unit zone (m_u) and solved to 3% optimality gap. First observation from Figure 6(a) is that, when access hubs are restricted to serve only one unit zone, as we increase the minimum number of hubs required per unit zone constraints from 1 to 2, total cost estimates reduces. This signifies that courier operational cost savings due to shared demand between 2 hubs for each unit zone is higher than the incurred extra deployment costs due to opening of new hubs and addition of modules to these hubs. However, as we increase m_u from 2 to 4, incurred deployment costs dominate over courier operation cost savings and the total cost estimates spikes up.

Secondly, when we allow access hubs to serve 2 unit zones, total cost estimates plummets for all m_u constraints. This can be ascribed to the fact that for most of the unit zones, the existing capacity in already deployed hub is used to fulfilling demand of one extra unit zone rather than deploying new hubs as depicted in Figure 6(d). For example, when we enforce at least 4 hubs near each unit zone, we see that the number of locations deployed drops from 13872 to 8000 as we allow access hubs to serve a maximum of 2 unit zones instead of 1.

Another general trend observed from Figure 6(a) is that as we make access hubs capable of serving more and more unit zones, total cost estimates drops significantly for all m_u constraints and the minimum total cost estimates is observed when we enforce atleast 3 hubs near each unit zone and each hub is capable of serving atmost 4 unit zones. 4417 locations were selected as potential locations in the case where minimal total cost estimates is obtained as depicted in Figure 5. This suggests that we should leverage on the capability of an access hub to serve more unit zones under the restrictions of its capacity to cut down on total cost estimates.

Figure 6(b) shows the travel distance per parcel against t_h and Figure 6(c) displays the distance travelled per parcel against t_h. For all t_h values, as we increase m_u, both travel time per parcel and distance travelled per parcel decreases because the inbound and outbound flow for each unit zone is split between the hubs, resulting in shorter courier routes as we leverage more hubs to serve unit zones.

5 Conclusion

This paper contributes to the literature by proposing an optimization model to design potential access hub networks, that need not be implemented as designed but can be fed into large scale network design and clustering models enabling them to be solved in appropriate time when accounting for more comprehensive inter-hub flow modelling. The framework suggests beginning by determining the set of unit zones that can be served by each candidate location. Then, we propose an optimization model using gross approximations of local hubs into priori estimates of cost and leveraging modular capacity deployments to find the set of potential locations that incurs minimum courier operations and deployment cost estimates while fulfilling the entire demand of all unit zones. These methods have been developed from realistic geometrical and operational approximations, making them readily applicable to different urban agglomerations.

It also assesses the potential of using such a solution in real-world context through an illustrative case inspired from a large parcel express carrier's operation. The analysis revealed that we should leverage on the capability of an access hub to serve more unit zones under its capacity restrictions to gain significant savings in operations and deployment cost estimates. Additionally, we can experiment with different values for threshold distance from hubs to study its impact on total cost estimates and other key indicators.

By specifying targets relative to the maximum number of unit zones that an access hub may serve, and the number of access hubs serving each zone, we can generate different sets of potential access hub locations. We can assess their computational solvability by feeding it to large scale design problem modelling comprehensive inter-hub flow and comparing its solving time and optimality gap with the baseline model starting with a large set of candidates as its input. In the context of mobile hubs, it can provide a set of potential locations from which actual locations can be selected for dynamic deployments of mobile hubs through framework proposed in Faugère et al. (2020).

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