HYPERCONNECTED CITY LOGISTICS: CAPILLARY NETWORK DESIGN AND MANAGEMENT

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By

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CAPILLARY NETWORK DESIGN AND MANAGEMENT

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To my late grandmother, who sparked my interest in engineering and with whom I dreamed of designing the most futuristic technologies.

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SUMMARY

In hyperconnected city logistics, this dissertation focuses on capillary networks which enable first-and-last mile logistics and fulfillment activities and customer interfaces with logistics systems. Capillary logistics networks are central to several innovations aiming to enable fast and convenient service to consumers while reducing cost and negative externalities associated with logistics activities in urban environments under the pressure of e-commerce growth. In this dissertation, we examine two types of urban capillary logistics networks: smart locker bank networks and access hub networks. Smart locker banks enable the aggregation of customer locations into a network of unattended pickup-and-delivery points. Access hubs serve as consolidation and transshipment points for logistics service providers at the neighborhood level.

Our objective is to provide a set of methods to design and manage capillary networks and identify key managerial insights to shape urban logistics. In doing so, we leverage concepts of the Physical Internet to examine modularity, hyperconnectivity and mobility solutions for smart locker bank and access hub networks. This work was shaped and supported by a research initiative entitled Data-Driven Design and Operation of Hyperconnected Intra-City Logistics Service Networks in collaboration with SF Express, a large parcel express carrier in China.

In Chapter 1, we introduce the conceptual framework and the terminology used throughout the dissertation. We define in more detail the concept of capillary logistics networks, smart locker banks and access hubs and their roles in the realm of urban parcel logistics.

In Chapter 2, we examine the essence of pickup and delivery networks and propose four design options for smart locker banks ranging from currently implemented designs to most mature implementation of Physical Internet concepts.

In Chapter 3, we introduce two problems: the fixed-configuration locker bank design

problem and the modular tower-based locker bank design problem. For both, we develop optimization-based methods that produce smart locker bank configurations and layouts from sets of probabilistic delivery scenarios. Results suggest that modular designs can perform just as well as custom fixed-configuration designs while being more flexible and reconfigurable.

In Chapter 4, we study a novel tactical optimization problem: the dynamic deployment of pooled storage capacity in an urban parcel network operating under space-time uncertainty. We characterize and model the access hub dynamic pooled capacity deployment problem as a two-stage stochastic program with synchronization of underlying operations through travel time estimates. We then propose a solution approach based on a rolling horizon algorithm with lookahead and a benders decomposition able to solve large scale instances of a real-sized megacity. Numerical results, inspired by the case of a large parcel express carrier, are provided to evaluate the computational performance of the proposed approach and suggest significant last-mile cost and capacity savings compared to a static capacity deployment strategy.

In Chapter 5, we examine the use of mobile access hub deployments to make dynamic use of urban space for logistics needs. We expand the understanding of characteristics influencing the economic and environmental efficiency of mobile access hub deployments by proposing a modeling framework and an integer program to assess the performance of mobile access hub deployments, and by studying the impact of a set of design parameters through synthetic cases and an illustrative case inspired from a large parcel express carrier's operations. Results indicate design flexibility relative to the location of hubs and pronounced advantages in highly variable environments. The illustrative case shows significant savings potential in terms of last-mile cost and time efficiency as well as environmental sustainability. It emphasizes a trade-off between operational efficiency and environmental sustainability that can be balanced to achieve global sustainability goals while being economically sound.

Finally, Chapter 6 summarizes takeaways from our work on capillary network design and management for urban parcel logistics, and identifies promising research avenues.

CHAPTER 1
INTRODUCTION AND CONCEPTUAL FRAMEWORK

This chapter presents the conceptual framework used throughout the dissertation thesis. It introduces concepts and nomenclature that constitute the basis of the different problems studied in following chapters, and present our contributions. This chapter is adapted from and extends a framework proposed in:

- B. Montreuil, S. Buckley, L. Faugère, R. Khir, S. Derhami, ”Urban Parcel Logistics Hub and Network Design: The Impact of Modularity and Hyperconnectivity,” in *15th IMHRC Proceedings*, 2018

1.1 Introduction

First-and-last-mile logistics is regarded as an essential yet highly expensive component of supply chains. In urban environments, this is partially caused by inherent inefficiencies such as traffic congestion and the disparity and accessibility of customer locations. As reported in [1], the combination of global urbanization, the transformation of the parcel logistics industry and the growth of e-commerce, and the ever-increasing desire for speed put on the need for innovation in designing, managing and operating first-and-last-mile activities in a sustainable and cost-efficient way.

City Logistics (CL) refers to a systemic view of activities related to freight movements within urban areas [2]. It encompasses innovations focusing on the mitigation of nuisances associated with transportation while supporting the economic and social development of cities. The Physical Internet (PI) is a set of concepts for freight transportation and logistics aiming to improve the economic, environmental and societal efficiency and sustainability of the way physical objects are moved, stored, realized, supplied and used all across the world [3]. City Logistics and the Physical Internet meet in the idea of Hyperconnected City Logistics introduced in [4] aiming to profoundly change freight transportation and logistics for increased economic, environmental and societal efficiency and sustainability. Capillary logistics networks enable first-and-last mile logistics and fulfillment activities and customer interfaces with logistics systems. This dissertation focuses on Hyperconnected City Logistics enabled innovations dealing with the movement of parcels in cities at the capillary level and leverages the conceptual framework presented in this chapter.

The parcel logistics industry is under strong transformative pressure to offer urban agglomerations, and notably the world's megacities, fast, precise and low-price delivery services that can reliably keep high service levels under high demand stochasticity and severe demand peaks and valleys. As a response to this pressure, logistics service providers are challenging the fundamental conceptual and technological pillars upon which they have built their urban service networks and operations, seeking better competitiveness through significantly higher capability, efficiency, and sustainability [4, 5, 6].

Parcel logistics systems, like the ones operated by DHL, FedEx, SF Express and UPS, are commonly structured around the standard hub-and-spoke network topology, with the term hub mainly denoting a sorting center [7] central to parcel flows. More specifically, a hub in such topology mostly refers to an intermediate point where parcels handling and transshipment can be centralized to tap into economies of scale and consequently reduce the per-unit cost of flow [8]. This single role view of facilities has been studied extensively in the literature to analyze and optimize the systems design and operations [9, 10, 11, 12, 13, 14]. While this view is beneficial from an analytical standpoint, a multi-level view is crucial to capture the hierarchical nature of parcel logistics system design as close to reality as possible. Embracing such a wider view creates more opportunities to improve the system under the conflicting objectives of achieving cost-effectiveness and providing tight urban service offerings such as X-minutes delivery.

Parcel logistic hubs currently play roles of customer interface, parcel sortation and / or crossdocking [15, 16, 17, 18, 19, 20]. The network topology linking such hubs is a key pillar of the performance of parcel logistics providers. Current factors enabling and / or limiting the performance of urban hub-and-spoke networks include, from an external perspective: travel, parking and building regulations; on-demand transport availability; the advent of connected and autonomous vehicle technologies (notably drones and droids); the growing Internet-of-Things enabled monitoring and traceability capabilities; the availability of smart transportation and delivery management systems; and, from an internal perspective: the reliance on service agreements based on cut-off times; the selection of vehicle sizes and routing logic; parcel sorting and consolidation policies; and handling unit loads.

This conceptual framework aims to apply modularity and hyperconnectivity concepts underpinning the Physical Internet (PI) [3, 21] to break away from currently dominating hub-and-spoke network topology in urban environments, toward a logistic web topology [21] based on multi-plane meshed networks interconnecting hubs adapted to each plane such that each hub acts as the source or destination of other hubs. The target potential benefits are to be obtained by the combination of features such as exploiting modular containers across the parcel logistics network; adapting the vehicles and handling equipment to take advantage of such containers; and exploiting live information about parcel pickup, delivery engagement, current location and time. The conceptual framework thus aims to contribute to designing the forthcoming generation of parcel logistic hubs and networks that are capable of supporting the trending goals of X-hours (ultimately X-minutes in an urban context) delivery services within megacities (e.g., Shanghai and New York) as well as much smaller cities across the world.

The remainder of this chapter is organized as follows. In section 1.2, a four-tier framework is presented to pixelize urban territories served by the parcel logistics system. In section 1.3, a corresponding parcel logistic web is introduced, depicted as a four-plane network of meshed logistics networks. The three higher planes of the logistic web correspond to a meshed inter hub network, with hubs specialized for each tier. In section 1.4, the focus is on on the capillary part of the parcel logistics web: pickup-and-delivery points and access hubs.

1.2 Multi-tier Pixelization of Urban Agglomerations

For parcel logistics purposes, a four-tier pixelization of urban agglomerations is proposed, quite in line with the practices of some logistics service providers while being innovative with its generic structuring of space, which facilitates efficient multi-party multimodal logistics and transportation operations. The four pixelization tiers are unit zones, local cells, areas, and the overall region, as shown in Figure 1.1. This pixelization extends at a higher level to regions clustered in blocks to span the world beyond the scope of urban agglomerations.

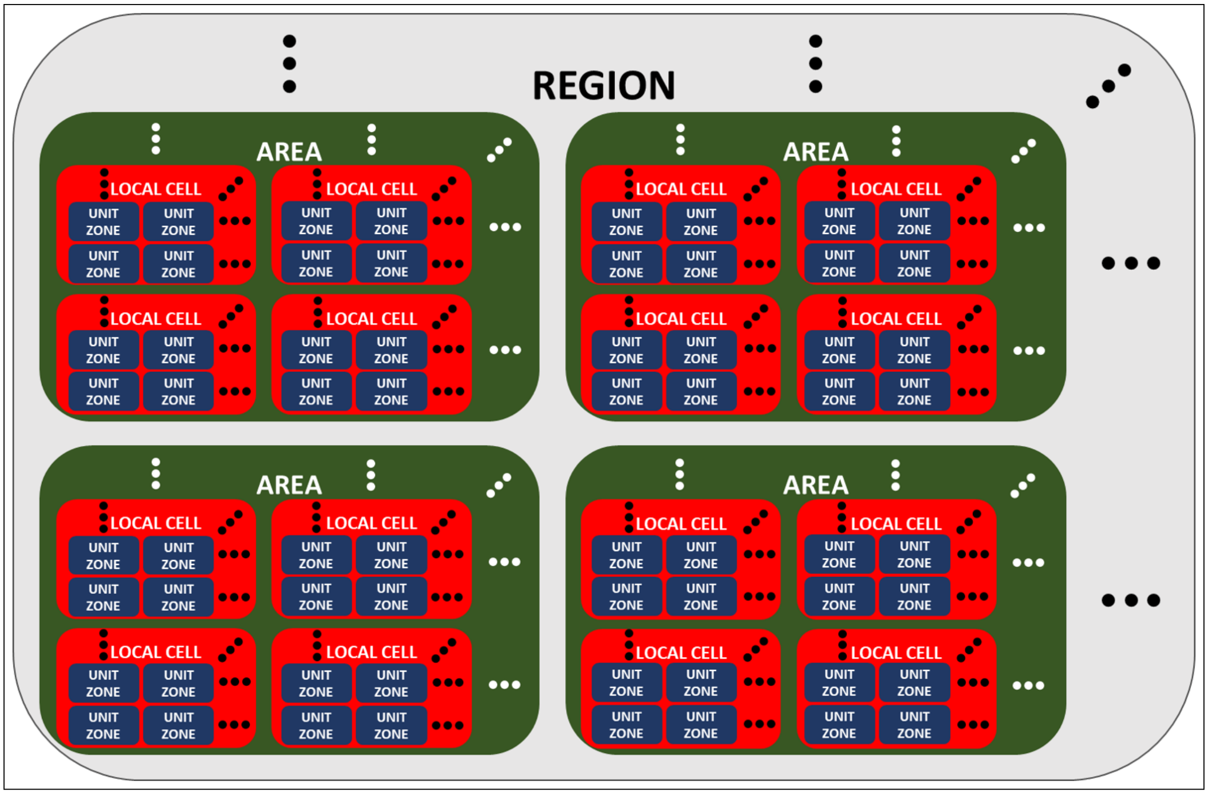

Figure 1.1: Urban Pixelization

The first tier decomposes the territory in contiguous unit zones that vary in size depending on expected demand density: examples include a suburban neighborhood, an urban community, a campus, an industrial park, a high-rise building or a set of stories of a high-rise building. Except when being part of a high-rise where height specification matters, a unit zone can usually be defined as a small polytope on the world map, or as a collage of the 3m x 3m squares recently defined by `www.what3words.com` to map the world and made easy to locate using a unique 3-word address. Several logistics service providers use the concept of unit zones within their organization, often assigning a single courier or a small team of couriers to be responsible for all their contracted pickups and deliveries within the zone. The second tier depicted in Figure 1.1 clusters sets of adjacent unit zones into local cells. The third tier clusters these local cells in areas, and the clustering of these areas defines the region in the fourth tier. The definitions of zones, cells, areas, and regions are not strictly bounded by geopolitical and natural borders and are subject to dynamic evolution as logistics demand and activity evolve in the hyperconnected cities, in line with the connectography work of [22].

1.3 Multi-plane Urban Parcel Logistics Web

In order to enable efficient and sustainable urban parcel logistics services, a multi-plane parcel logistic web is proposed interconnecting meshed transportation networks along four planes, as depicted in Figure 1.2: plane 0: O-D points network, linking origin-destination customer locations and pickup-and-delivery points; plane 1: inter-zone network; plane 2: inter-cell network; plane 3: inter-area network. On a broader scale, this urban parcel logistic web is connected to higher-plane meshed networks, such as inter-region networks (plane 4) and inter-block networks (plane 5), allowing parcels to flow from any zone of any city to any zone of any city, whatever their region and block in the world.

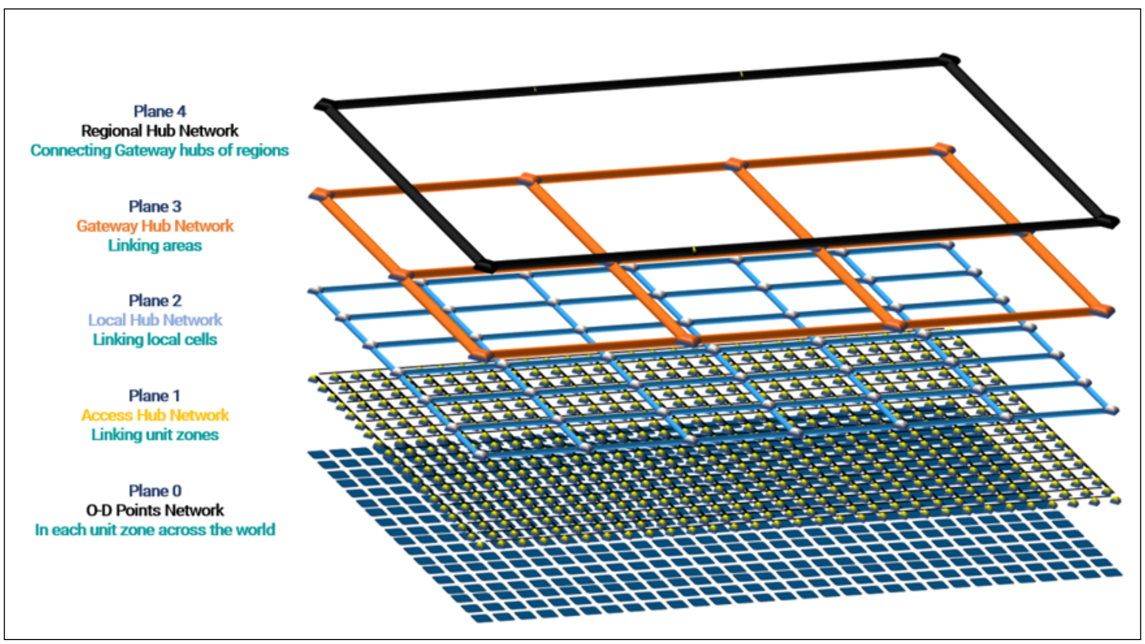

Figure 1.2: Urban Parcel Logistic Web

The urban parcel logistic web's nodes are defined as pickup-and-delivery locations within zones, access hubs located at the intersection of neighboring zones, local hubs at the intersection of neighboring local cells, and gateway hubs at the intersection of neighboring areas.

Plane 0 of the logistic web is the inter-P/D network linking the customer pickup-and-delivery locations: e.g., household, office, store, factory, parking, smart locker bank, and package rooms. Each zone is directly connected to one or more access hubs. These are concurrently connected to the inter-P/D network and interconnected through the meshed plane-1 inter-zone network.

The inter-zone network facilitates direct transfer of parcels between sources and destinations in nearby zones. Local cells have each been illustratively defined in Figure 1.1 as a rectangular cluster of unit zones while each area has been similarly defined as a rectangular cluster of local cells. Each local cell and each area is connected externally to four hubs, respectively local hubs and gateway hubs. At each local hub location also lays an adjacent access hub so as to ease the linking of the plane-1 inter-zone network and plane-2 inter-cell network. Similarly, at each gateway hub location also lays an adjacent local hub, so as to ease the linking of the plane-2 inter-cell network and plane-3 inter-area network. Gateway hubs are the main interfaces between areas of a megacity. They act as the main hubs for consolidating inbound and outbound flows across the regions (i.e., between neighboring cities).

All possible transportation infrastructure networks are to be leveraged for the flow of parcels between P/D locations, access hubs, and local hubs. This includes streets, avenues, backstreets, biking / walking trails, corridors, elevators, and local drone airways. In higher planes, there is gradually more opportunity to utilize the network of boulevards and highways, rapid transit system and railway infrastructures, waterways and inter-airport airways to flow parcels between local hubs, gateways hubs, and eventually, regional hubs and global hubs. Consequently, depending on the travel locations and distances, and the visiting planes and networks, multiple modes can be leveraged, including walking, bikes, scooters, droids, drones, electric urban vehicles, trucks, tramways, subways, buses, barges, ships, rail-cars, airplanes, and airships.

Throughout the parcel logistic web, multiple transportation service providers may be leveraged to move parcels in a synchromodal way from the source to the destination. It is also possible that different service providers operate the logistic hubs in a territory. Hence, the resulting parcel logistic web is interconnecting multi-plane, multi-party, and multimodal meshed logistic networks.

1.4 Capillary Logistics Networks

Capillary logistics networks enable first-and-last mile logistics and fulfillment activities and customer interfaces with logistics systems. In particular, they enable local interfaces to logistics networks by providing locations (e.g. stores, showrooms, storage facilities, mobile hubs, collection points) where logistics and fulfillment activities can take place (e.g. transshipment, storage, exchange of goods). They can be seen as an analogy to capillary networks in the human body which are composed of capillary blood vessels, site of exchange of many substances at a local level, or telecommunication capillary networks which are local area networks that act as an extension of the wide-area links (e.g. cellular network) to provide connectivity.

In the context of urban parcel logistics examined in this dissertation, parcels are flowing from an origin to a known destination and do not require storage from a fulfillment point of view. Goods are collected from consignees and enter the logistics provider network (pickup activities), move throughout the network (transshipment activities), and exit the logistics network to be delivered to recipients (delivery activities). Within the proposed multi-plane urban parcel logistics web, plane 0 (pickup-and-delivery network) and plane

1 (access hub network) constitute a capillary network of hubs dedicated to parcel logistics. This dissertation deals with select design and management problems for two types of logistics facilities constituting capillary networks for urban parcel logistics: (1) smart locker banks as pickup-and-delivery points and (2) access hubs.

1.4.1 Pickup-and-Delivery Points

Pickup-and-delivery points are locations where parcel logistics services originate and / or terminate. They are typically home or office locations, custom locations, or consolidation locations requiring customer movement.

One of the burdens of home and office delivery is the risk of unsuccessful delivery due to recipient absence [23, 24]. A few innovations for unattended delivery options such as secure parcel boxes and controlled authorized access have been developed to mitigate risks of delivery failure and doorstep theft while giving time flexibility to logistics activities with respect to recipients availability.

Custom locations are an alternative to home or office delivery where goods are delivered to an predetermined alternative location where the recipient will be located for a specific time window. Innovations in this area include ship-to-me [6] and trunk delivery [5], both solutions that require tight delivery scheduling and synchronization with the given time window and precise delivery location information (e.g. precise meeting point, car make model and license plate number).

Delivery to consolidation locations have also emerged as an alternative eliminating the risk of failed delivery, offering consolidation opportunities, but requiring customers to collect their goods themselves. Example of consolidation locations are staffed point-of-sales (e.g. postal offices, partnered shop network) and unattended collection points such as smart lockers. From a logistics perspective, such solutions have the advantage of reducing the number of different delivery locations by clustering sets of customers into fixed, known locations to be visited likely every day, thus improving first-and-last-mile logistics efficiency through consolidation [25, 26]. Moreover, consolidation points have been received as a good option for customers who are willing to collect their goods from convenient locations [27, 28]. There are several challenges when it comes to designing and managing pickup-and-delivery point networks including location-allocation, routing and locker layout problems. In this thesis, selected challenges on the design of smart locker networks are examined in chapters 2 and 3.

1.4.2 Access Hubs

Access hubs are entry points to the multi-plane urban parcel logistics web, located close to pickup-and-delivery points, supporting relay-based first-and-last-mile activities by enabling the decoupling of local transportation activities from the rest of the urban distribution chain. Access hubs are consolidation and transshipment locations between couriers performing pickup and delivery services at the unit zone level and riders transporting parcels between local hubs and a set of access hubs a the local cell level. Although in particular cases, such as e-commerce shipments from large e-retailers, entry in the multi-plane logistic web may occur at higher level hubs (e.g. local hubs, gateway hubs) due to large volumes, the focus here is on entry and exit through access hubs which is relevant to the majority of deliveries and a large customer segment of pickups (e.g. non-retail businesses, individuals).

As reported in [29], several micro-consolidation initiatives have been proposed to down-scale the consolidation effort by bundling goods at the neighborhood level using capillary networks of hubs located much closer to pickup-and-delivery points, defined here as access hubs. Examples of such initiatives are satellite platforms (e.g. [30]), micro-consolidation centers (e.g. [31]), mobile depots (e.g. [32]), and micro-depots [33].

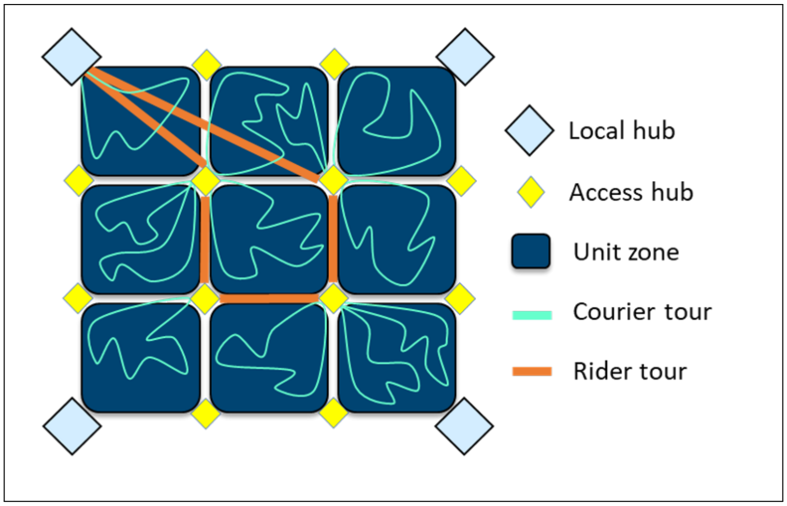

Figure 1.3: Access Hubs as Micro-transshipment Points

The most significant benefit from using access hub networks is the decoupling of first-and-last mile transportation from the rest of logistics activities. It enables couriers to be solely dedicated to first and last mile activities for more effective operations (including the use of light-weight vehicles), to offer more flexible pickup and delivery options by temporarily storing parcels close to demand locations anticipating the ideal time for delivery or outbound activities (e.g. moving packages nearby delivery locations at night), and to foster consolidation opportunities as early as parcels are being picked up.

From a technology point of view, several options can be considered to serve as access hub including simple storage sheds (e.g. `www.thehubcompany.eu`), smart locker based solutions similar to pickup-and-delivery points (e.g. [34]), and trailers (e.g. [35]). There are several challenges when it comes to designing and managing access hub networks including location-allocation, routing, consolidation and capacity management problems. In this thesis, selected challenges on the deployment of access hub networks are examined in chapters 4 and 5.

1.5 Contributions

This dissertation thesis contributes to the urban parcel logistics literature by examining the design and management of two constituents of capillary networks for urban parcel logistics: smart locker banks and access hubs.

In Chapter 2, we examine the essence of pickup and delivery networks and propose and compare four design options for smart locker banks ranging from currently implemented designs to most mature implementation of Physical Internet concepts.

In Chapter 3, we introduce two problems: the fixed configuration locker bank design problem and the modular tower-based locker bank design problem. For both, we develop optimization based methods that produce smart locker bank configuration and layout from sets of probabilistic delivery scenarios. Our primary contributions are as follows:

- Introduction of an optimization model for fixed configuration locker bank design
- Introduction of an optimization model for modular tower based locker bank design
- Empirical investigation comparing both design methods

Results suggest that modular designs can perform just as well as custom fixed configuration designs while being more flexible and reconfigurable.

In Chapter 4, we study a novel tactical optimization problem: the dynamic deployment of pooled storage capacity in an urban parcel network operating under space-time uncertainty. Our contribution is threefold:

- Characterization of a new tactical problem, for capacity deployment, motivated by dynamic aspects of urban parcel logistics needs
- Modeling of the access hub dynamic pooled capacity deployment problem as a two-stage stochastic program with synchronization of underlying operations through travel time estimates

- Design of a solution approach based on a rolling horizon algorithm with lookahead and a benders decomposition able to solve large scale instances of a real-sized megacity

Numerical results, inspired by the case of a large parcel express carrier, are provided to evaluate the computational performance of the proposed approach and suggest up to 28% last-mile cost savings and 26% access hub capacity savings compared to a static capacity deployment strategy.

In Chapter 5, we examine the use of mobile access hub deployments to make dynamic use of urban space for logistics needs in areas where it is not possible to have logistics facilities such as access hubs due to high population density, real estate constraints, or local government restrictions. We expand the understanding of characteristics influencing the economic and environmental efficiency of mobile access hub deployments by:

- Proposing a modeling framework and an integer program to assess the economic, time efficiency and environmental performance of mobile access hub deployments for urban parcel logistics

- Studying the impact of a set of design parameters through synthetic cases and an illustrative case inspired from a large parcel express carrier's operations

Results indicate design flexibility relative to the location of hubs and pronounced advantages in highly variable environments. The illustrative case shows significant savings potential in terms of cost and time efficiency as well as environmental sustainability. It emphasizes a trade-off between operational efficiency and environmental sustainability that can be balanced to achieve global sustainability goals while being economically sound.

CHAPTER 2

HYPERCONNECTED PICKUP AND DELIVERY LOCKER NETWORKS

This chapter examines smart lockers as pickup-and-delivery points and proposes alternative design options from simple fixed to designs to more flexible ones leveraging concepts from the physical internet.

The work presented in this chapter has been published in the proceedings of *International Physical Internet Conference* under the following reference:

- L. Faugère and B. Montreuil, ”Hyperconnected pickup and delivery locker networks”, in Proceedings of the 4th International Physical Internet Conference, Graz, Austria, 2017

2.1 Introduction

The courier, express & parcel industrys global market size is growing. [36] notably reported a growth rate of 5% in value over the 2013-2020 horizon, ranging from 5% in Western Europe and South America to up to 9% and 15% respectively in North America and Asia Pacific markets. As the world is experiencing a global urbanization that is projected to reach 66% of the population by 2050 (currently 54%) with highs in North America (82%), Latin America and the Caribbean (80%), and Europe (73%) [37], urban areas will experience a dramatic increase in freight deliveries. This could lead to unsustainable traffic congestion, greenhouse gas emissions and noise and air pollution at unprecedented levels [38]. Many smart city initiatives (e.g. `www.smartcitiescouncil.com`, `www.worldsmartcity.org`, and the U.S. Department of Transportations Smart City Challenge) aim at understanding the logistics and supply chain challenges of tomorrows city logistics, developing new application and supply chain innovations in delivery channel, distribution networks, and transportation modes.

The currently emerging pick-at-locker (P@L) business-to-consumer flow alternative, materialized by smart lockers, presents the advantages of being a simple and unstaffed delivery option [6] suited for most deliveries (typically small to medium parcels requiring no temperature control). Smart locker banks grouping an unattended set of pickup and delivery lockers are a promising solution for last-mile parcel delivery and return, focusing on unsuccessful deliveries and consolidation opportunities. P@L networks aim at offering convenient and secure pickup locations for consumers, while potentially driving delivery costs down by reducing the number of delivery points and avoiding unsuccessful deliveries leading to multiple delivery attempts. Such networks have the potential of eliminating unsuccessful deliveries, and reducing delivery costs, city congestion, and greenhouse gas emissions [39]. This solution is globally emerging and already proven successful in European and Asian markets as a cheaper alternative to home delivery. Figure 1 shows examples of smart locker banks. Automated and equipped with interactive modules, they allow pickups and deliveries to be performed in a few minutes.

One of the challenges of deploying a network of pickup and delivery lockers as an alternative to home delivery is expressed through the uncertainty of the demand. A variable number of packages of a wide range of sizes are to be delivered in a capacity-limited locker bank, making the design and configuration of each bank critical to its capacity (number of lockers and their respective dimensions). In its current form, a smart locker bank has a fixed configuration of lockers of different predefined sizes, aiming at balancing service levels and fabrication costs. It is subject to obsolescence as its design is not flexible. It may also suffer from low space utilization, due to the fact that packages rarely take all the space available in one locker. Indeed, as only a few different sizes of lockers are present in the smart locker banks from Figure 2.1, it is expected that most packages

Figure 2.1: Illustration of Current Smart Locker Banks (source: photographs by authors)

will not exactly match with the space available in one locker, rapidly decreasing the space utilization of the bank.

This chapter aims at conceptualizing smart locker bank designs to meet the challenges toward achieving omnichannel logistics efficiently and sustainably while meeting the timely expectations of clients, leveraging key concepts of the Physical Internet [3]. After the essence of P/D locker networks is defined, four designs are presented in this chapter, ranging from current practices to more mature Physical Internet (PI) concepts implementation.

2.2 Hyperconnected Pickup & Delivery Locker Networks

Smart locker banks grouping an unattended set of pickup-and-delivery lockers bring an alternative to home delivery. Currently mostly used for goods ordered through e-commerce channels, providing consumers convenient pickup locations, they could also be used to pre-position items in neighborhood leveraging smart demand predictive analytics. Current customers expectations in terms of delivery lead time and pickup conve-

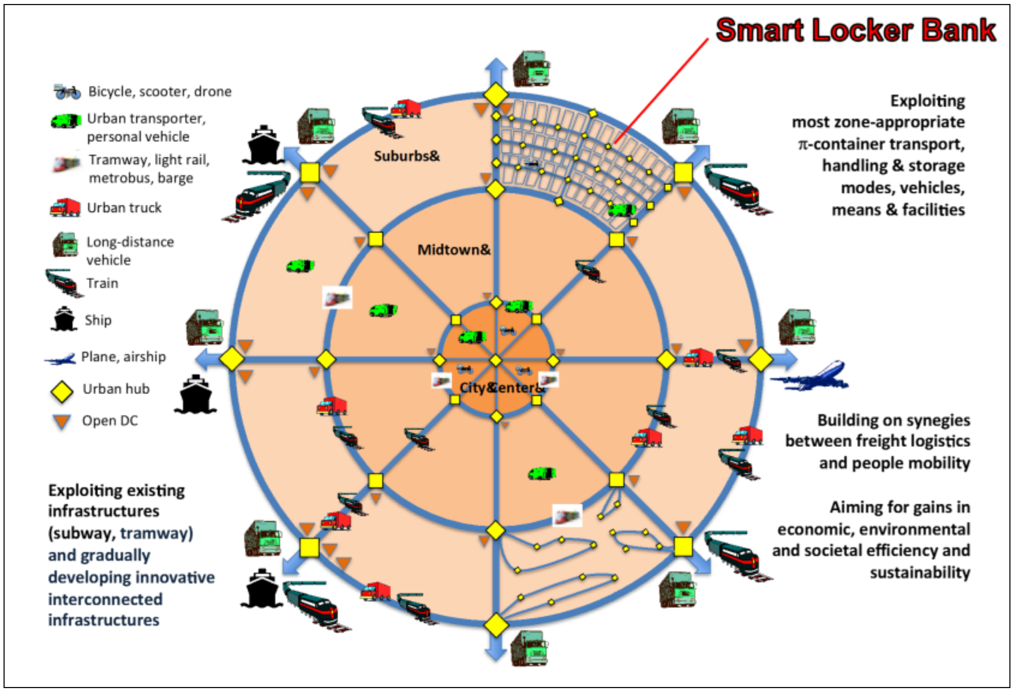

Figure 2.2: PI Enabled Hyperconnected City Logistics, Highlighting the Role of Smart Locker Banks (Adapted from [4])

nience lead to the need for up to multiple smart locker banks per neighborhood [6]. Thus, networks of P/D lockers are positioned as a last logistics step before packages reach consumers homes, and are distributed at the neighborhood level as depicted in Figure 2.2 in the context of Physical Internet enabled hyperconnected city logistics [4].

Note that smart locker banks are one of the possible alternatives to home delivery proposed in the Physical Internet concepts in the context of omnichannel business-to-consumer logistics and supply chain [6] which aims at letting customers order anytime from anywhere, in person or through digital and mobile devices, and be fulfilled at their convenience, delivered or picked up at their preferred time and location. As shown in Figure 2.3, pick-at-drive and pick-at-store are two other alternatives requiring the final consumer to pick up their goods at some facility. However, smart locker bank networks provide a better level of convenience for some consumers, as they are distributed in neighborhoods, thus closer to homes, and are unattended, mostly accessible at any time.

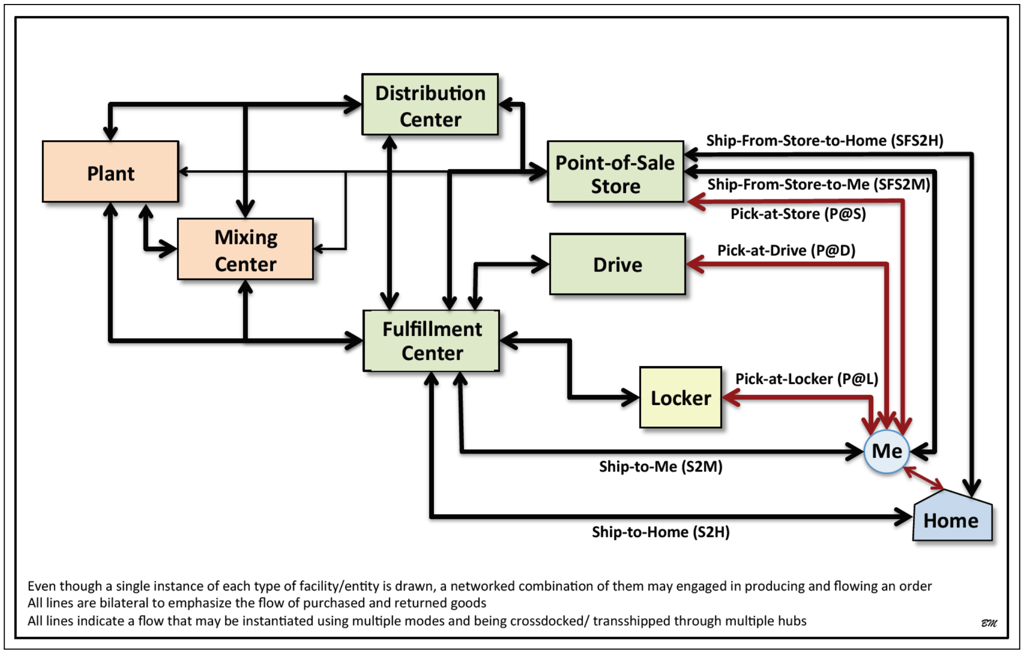

Figure 2.3: Omnichannel B2C Logistics and Supply Chains Alternatives (Source: [6])

From a logistic carrier perspective, smart locker banks allow consolidation of deliveries into predictable delivery locations. As P/D points are distributed over a known network, simpler and more efficient routing strategies can be developed to drive both delivery cost and delivery resource needs down, while increasing efficiencies. The potential elimination of unsuccessful deliveries and the need for less delivery resources could dramatically decrease the miles traveled by logistic carriers within urban environment, thus positively impacting city congestion and greenhouse gas emissions.

Another important aspect of the use of smart locker banks as P/D points in an urban environment is the operating model and ownership associated with lockers. Because deploying an extensive network to cover a city relies on a significant level of infrastructure investment (one bank representing a few ten-thousand USD), and operations cost (maintenance, land cost, utilities, insurance, etc.), one may consider opening a locker to multiple parties through partnerships or charging a per-use cost. Moreover, a multi-operator model has the potential to be more efficient as managing aggregated variations of demand

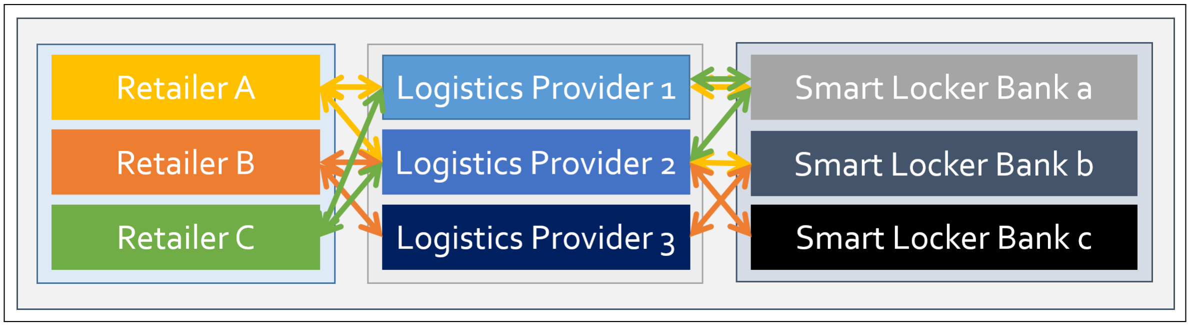

Figure 2.4: Hyperconnected Multi-Operator Pickup-and-Delivery Lockers (Adapted from [40])

could lead to less capacity required than managing variations of demand individually for each player. Also, as smart locker banks are integrated in public spaces and infrastructures, it seems unlikely that municipalities and city planners allow multiple players to deploy their own private network within the same neighborhood. A multi-operator operations model is illustrated in Figure 2.4 for e-commerce supply chains composed of multiple retailers, using a set of logistic providers and open pickup and delivery points. We may call such a network of smart locker banks a hyperconnected P/D locker network.

2.3 Current Practices: Fixed-Configuration Smart Locker Banks

As depicted in Figure 2.5, smart locker banks in their current form are sets of P/D lockers of predefined sizes arranged in a fixed-configuration bank. Having a network of such banks enables relatively simple implementation. In general the efficiency of a fixed-configuration locker bank shall be highly dependable on (1) homogeneous and consistent demand over time and (2) predictive capability in regard to demand and its evolution, insuring that it may be rightly configured and that this configuration will remain well fitting over time.

The main advantages of this design are:

- It has opportunities for economies of scale relative to design and manufacture stan-

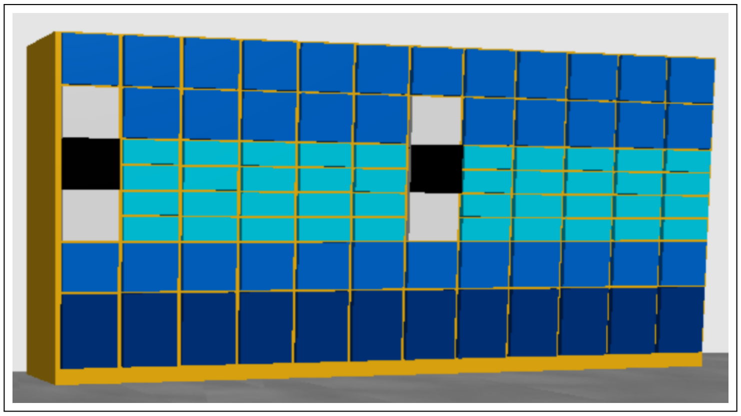

Figure 2.5: Illustration of Current Smart Locker Bank

dard banks, and to locate them into a network

- It represents a one-time implementation cost. The network being fixed, there is no need for redesign of the smart locker banks. Moving units to different locations is still possible but will not require structural modifications

While advantageous in some ways as expressed above, a fixed configuration is constraining when filling up the smart locker bank with packages. Success of delivery will depend on the availability of a locker of sufficient dimensions at the time of the delivery. This is the origin of the main disadvantages of this design:

- It may rapidly become under or over capacitated. Global level of demand may evolve over time, resulting in substantially more or less number of packages to be delivered at a smart locker bank. In such a situation, over time, the design will become obsolete and will see its performance or space efficiency decrease

- It may not adapt to variation of delivery patterns, punctually and over time, resulting in different package-size mixes. For example, a smart locker bank expecting primarily small-dimension packages will perform well as long as the size mix of packages being delivered stays relatively stable with a strong majority of smaller packages. If the mix changes and the packages being delivered get substantially bigger, the smart locker bank might not have enough lockers of adequate dimensions to receive the new demand, and might have a set of lockers unutilized, too small for the new delivery pattern

While advantageous in terms of implementation, fixed-capacity smart locker banks can be inadequate when demand evolves or is difficult to predict. The challenge of capacity management and configuration arises, which is the backbone of the next design proposed.

2.4 Leveraging Modular Towers

Contrasting with the fixed configuration of section 2.3, we highlight in Figure 2.6 a smart locker bank conceived as a set of modular towers. The HiveBox locker banks, implemented in large quantities across Shenzhen in China, leverage such modular towers. In Figure 2.6, each tower is the same width and height, with two columns of lockers having all the same width. The locker bank implemented as a concatenation of such towers. The height of a tower depends mostly on human constraints, as each locker must remain reachable within acceptable levels of effort. The width of a column in a tower may be variable, with the width of its lockers adapted to the column width. This requires more flexible manufacturing than standard-width lockers, columns and towers.

Using tower modularity, the global capacity of a smart locker bank can be adjusted over time by adding/removing modules, within the overall space constraints of the site. Figure 2.7 shows how the capacity of a smart locker bank can be increased by plugging an additional column module. Note that additional modules can come from a separate source, or simply be moved from a smart locker bank to another within the network when rebalancing its capacity.

This design enables dynamic capacity management over a network of smart locker

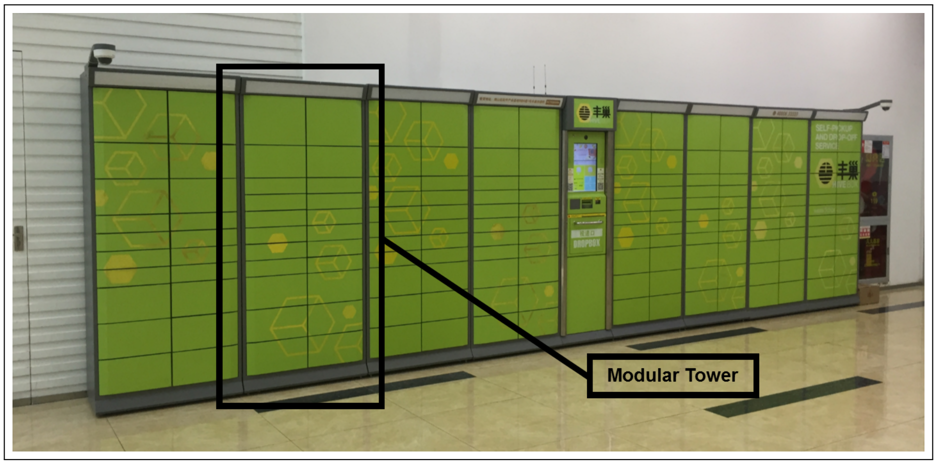

Figure 2.6: HiveBox Smart Locker Bank, Shenzhen, China, leveraging Modular Towers (Source: Photographs by Authors)

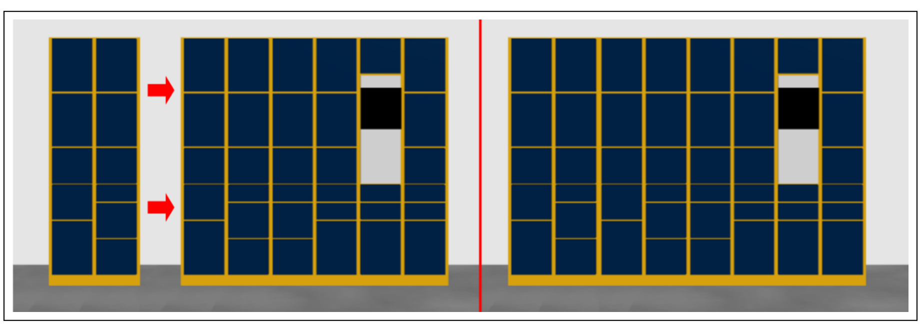

Figure 2.7: Increasing the Capacity of a Smart Locker Bank by Adding a Modular Tower

banks. Smart locker banks with Modular Towers thus offer the following main advantages:

- It can adapt to variations of global demand in modular tower increments: When adequately managed, the networks capacity can be adjusted over time by adding / removing column modules at specific smart locker locations
- It can be advantageous in highly seasonal markets: For instance, a stock of modular towers can be maintained to enable substantially increase of the networks capacity during peak seasons (Christmas, cyber-Monday, etc.) and ensure minimal footprint during valley seasons

Note that it would require a slightly more complex system, with the following main disadvantages:

- Assuming significant supply times from modular tower suppliers, it requires a modular tower inventory management system: modular towers must be held in inventory and distributed over the network in a timely manner as needed; This could represent a significantly high inventory, especially if many types of column modules of different configuration of lockers are held in inventory to enable greater capacity flexibility
- It needs capacity management policy and frequency: the frequency at which the capacity of the network is adjusted must be defined as well as the policy ruling the addition and removal of tower modules at a specific location; This would also require high visibility on the current configuration of the network and the available inventory
- It requires distribution capabilities to transport and install or remove tower modules: these tower modules may be heavy and require special handling equipment

- It can difficultly adapt to variations of demand patterns, such as evolution of the mix of package sizes deployed in the locker banks

While now accounting for variations of global demand, smart locker banks with modular towers have limited advantages when the mix of package sizes also varies. The next proposed design is adding a level of modularity to account for mix changes.

2.5 Leveraging Modular Lockers

Taking modularity to the next level, smart locker banks can be composed of individual modular lockers, whether or not the banks leverage modular towers. The locker modules must (1) have modular sizes (as the well-known Lego blocks) harmonized to the bank and modular tower structure dimensions, and (2) have modular connectors enabling their easy addition to, and removal from, a locker bank or tower.
Modular lockers enable a fine-granularity adjustment of the capacity of each locker bank, allowing modifications of the entire configuration, as in illustrated in Figure 2.8. A locker bank design leveraging locker modularity offers the following main advantages:

- It can adapt to variations of global demand, both in terms of volume and mix, within the limits of the site, the bank structure and / or the tower modules

- It can be advantageous in highly seasonal markets: a stock of modular lockers can be maintained to enable substantially increase of the networks capacity during peak seasons and ensure minimal footprint during valley seasons (subject to the same limitations as above

- It is capable of accounting for variations of delivery patterns: It has the capabilities to adjust its configuration to the change of package size mix over time by adjusting the number of lockers of each modular dimension

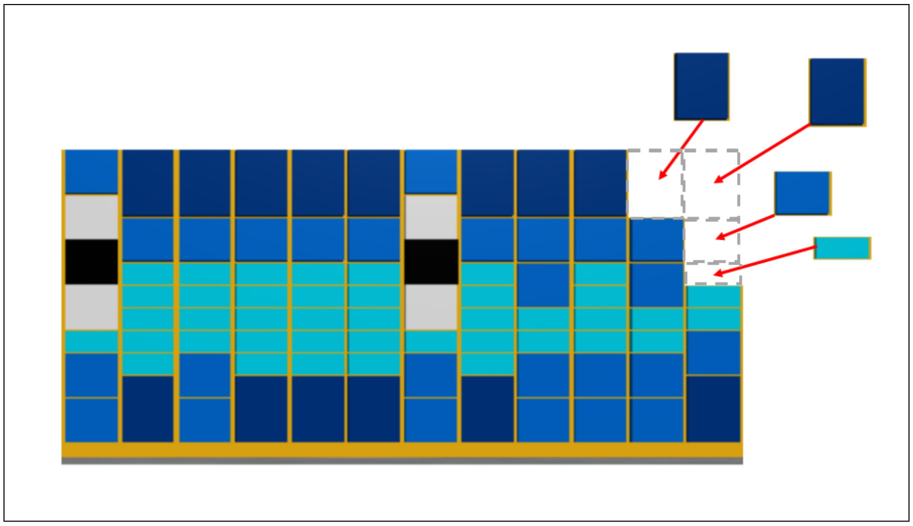

Figure 2.8: Illustration of a Smart Locker Bank leveraging Modular Lockers

A smart locker bank design using modular lockers increases the supporting system complexity and has the following main disadvantages:

- Assuming significant supply times from modular locker suppliers, it requires a modular locker inventory management; In this case, modules are smaller than towers yet have a variety of modular sizes
- It needs capacity management policy and frequency, as induced by modular towers, yet at a more granular level
- It requires distribution capabilities to transport and install/remove locker modules

As with modular towers, modular lockers can come from a pooled inventory or be exchanged between smart locker banks when rebalancing the capacity of the entire network.

Note that smart locker banks with modular towers and modular lockers have the potential to mitigate the disadvantages of fixed-configuration locker banks by allowing for capacity management of the network to adjust to variability of demand patterns (global demand and package sizes mix) but are more complex, requiring dedicated inventory, capacity management and distribution systems. Indeed, tower and / or locker modules must be stored, transported, and installed / removed, and the frequency and policy ruling these manipulations must be predefined. It may require a significant amount of resources to manage such a system.

The next proposed design aims at mitigating the resources required by leveraging Physical Internet handling containers [41].

2.6 Leveraging Physical Internet Handling Containers

The use of Physical Internet containers as a standard for transportation and storage of physical goods at all levels of supply chains promises significant improvement in space-time utilization of transportation, handling and storage means. Moreover, PI-containers and their modular dimensions bring opportunities to develop new logistics designs rethinking the way we deal with physical goods. This section introduces the use of PI-containers as pickup and delivery lockers, as an alternative to modular lockers and towers: the PI-containers become smart mobile lockers.

In the previous sections, the basic underlying assumption has been that goods to be picked up or deposited were to be done so by putting them from / into a fixed locker, as it commonly used in smart locker banks across the world (e.g. Figures 2.1 and 2.6). Here, the proposal is for encapsulating the goods into smart modular PI-containers and using these PI-containers as smart lockers. PI-container lockers can be interlocked to each other, stacked on top of each other or snapped to a simple grid-shape bank structure, using basic Physical Internet concepts and principles as proposed by [42].

Smart locker banks have a fixed configuration of lockers of different predefined sizes, aiming at balancing service levels and fabrication costs. The modular designs proposed in preceding sections give some flexibility and enable to modify the configuration of the banks of lockers according to the capacity and configuration management frequency, but

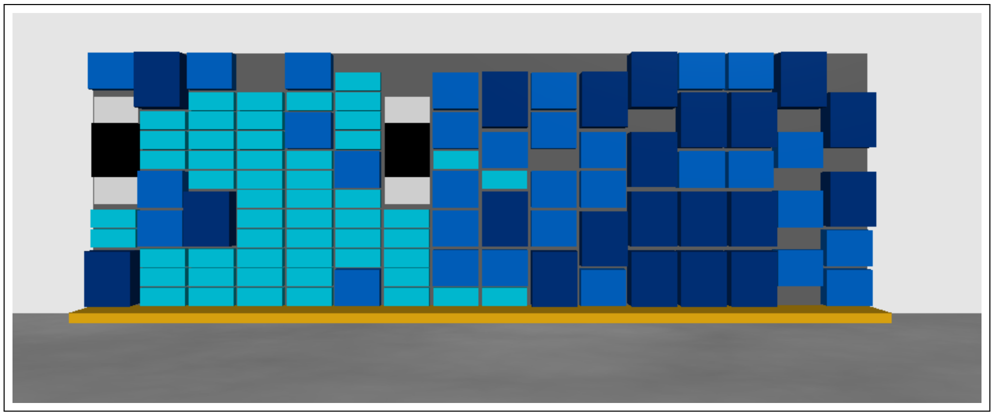

Figure 2.9: Illustration of a PI-Container Based Smart Locker Bank at Some Punctual Time

are still fixed between the reconfiguration periods. This yields designs good enough for a wide variety of delivery scenarios, but optimal for none, resulting in non-optimal utilization efficiencies and service levels.

A design using PI-containers as lockers, leveraging their interlocked stacking and / or grid-snapping capabilities, has the potential of eliminating volume utilization inefficiencies and of offering better service levels to users, reaching toward near optimality for each demand scenario. Per the proposed concept, smart PI-locker banks, instead of being composed of a set of lockers, are now composed of a basis, a grid-wall of predetermined surface to which PI-containers are dynamically snapped as shown in Figure 2.9. Possible accessories that can be snapped to the grid-wall include interactive modules, protection roof, security cameras and lights.

2.6.1 Physical Internet Handling Containers

Introduced as one of the core concepts of the Physical Internet by [3], the exploitation of smart modular PI containers represents one of the main technological component of the Physical Internet encapsulation of goods framework. [41] have categorized three levels of PI containers: the PI transport, handling and packaging containers, respectively nicknamed PI-pods, PI-boxes and PI-packs. [43] and [44] have focused on the PI-boxes that are notably targeted to replace contemporary totes, boxes and cases as core handling unit loads. In the proposed pickup and delivery locker bank architecture, PI-boxes are planned to be used as smart mobile lockers.

The fast snapping and interlocking capabilities of PI-containers is the foundation of the proposed design, as PI-boxes replace current lockers. Indeed, as they can be easily snapped to a grid-wall, a large number of configurations is possible. In order to be practically accessible, an interspace between consecutive PI-boxes is represented in Figure 2.9, allowing extracting a specific PI-box when surrounded by others. Arguing that current physical lockers also are separated by some space required by the support structure of the whole smart locker bank, and by the mounts of the doors, it is conservative to assume these interspaces to be of similar scale.

The structure of PI-boxes, being robust, reliable and sealable, as well as their communication capabilities and their eco-friendly nature, make them suitable to be used as efficient and safe pickup and delivery lockers, protecting physical goods from weather conditions and theft, while ensuring monitoring and communication of its content to logistics systems.

2.6.2 Pickup and Delivery Mechanisms

To perform a delivery or a return, a logistic service provider or a customer potentially just have to snap a PI-box at an empty grid position. The exact position at which a PI-box is assigned can depend on a predefined policy, real-time optimization, or be chosen by the person at the time of the delivery to the grid-wall. It is also possible for a return or delivery of loose goods to be made in an empty PI-box, which would have been left snapped on the grid-wall from a previous delivery. While the snapping mechanism requires the overcoming of technology challenges (notably electronic and mechanical safety), it potentially enables the following pickup options:

- The customer opens the front face of the PI-box, and picks up the ordered goods. In this case, empty PI-boxes will be picked-up by the logistic service provider during the following delivery and then redistributed in the open system

- The customer picks up and brings the whole PI-box home, and later redistributes it in the system (at a store, click-and-collect drive, locker bank, etc.) or uses it for shipping or returning other goods

2.6.3 Capacity Modularity

The number, size and configuration of PI-boxes constituting the goods storage in such an architecture is variable and offers great flexibility. Additionally, the grid-wall itself can be a modular element adding capacity flexibility. Panels constituting a grid-wall can be added / removed, thus expanding / reducing the area of the zone on which PI-boxes can be snapped, thus increasing / decreasing the modular capacity of the smart PI-locker bank. This design offers the following main advantages:

- Thanks to the snapping capabilities of PI-boxes, it has the potential of significantly improving the handling efficiency and dynamics of deliveries and pickups at smart locker banks, while ensuring the security of goods

- Its configuration is decided as deliveries and returns occur, when PI-boxes are being snapped to the grid-wall

- It is highly flexible: its configuration and global capacity can adapt seamlessly in real time to variations and seasonality of demand and delivery patterns

- It does not require locker bank specific resources; PI-boxes are resources moving across different tiers of the supply chain; they are thus to be managed globally

- It is expected to have minimal footprint and to require less upfront investment

As this design implements a more mature level of Physical Internet concepts, it has the current following main disadvantages:

- It requires the implementation of PI-containers, and notably PI-boxes, as a mean of transportation, handling and storage in the omnichannel business-to-consumer industry

- Regarding capacity management, Physical Internet induced hyperconnectivity is essential to ensure the dynamic circulation of PI-containers within the network of smart PI-locker banks, as well as more globally, at an inter-network level

- It requires to face technology challenges in ensuring the security of goods while stored at a P/D point. The PI-boxes must be securely snapped to the grid-wall, be sealed and strong enough to protect goods from damages and theft, and be convenient for handling and transportation (ergonomics, weight)

2.7 Conclusion

Combining Physical Internet inspired hyperconnected city logistics and hyperconnected omnichannel logistics perspective, this chapter contributes to the development of last-mile delivery alternatives in the context of omnichannel supply chains by introducing and contrasting a set of hyperconnected pickup-and-delivery locker network design options for efficiently and sustainably achieving fast and convenient business-to-consumer pickups and deliveries.

The options range from current practice, such as fixed configuration locker banks, to those applicable in a mature implementation of the Physical Internet concepts. The modular tower option has already begun to be used in practice while modular lockers can be fully implemented in the short-term horizon. The last option requires several steps as it relies on the use of Physical Internet handling containers (PI-boxes) as smart mobile modular lockers. The proposed designs can provide strategic visions on the evolution of dynamics of last-mile delivery in an urban environment. Overall, four concepts for hyperconnected pickup and delivery locker network designs are proposed, with advantages and disadvantages summarized in Table 2.1.

Overall, the following challenges need to be addressed for widespread implementation of hyperconnected smart pickup-and-delivery locker bank networks for omnichannel business-to-consumer supply chains:

- Engineering design: methods for designing hyperconnected pickup and delivery lockers, locker banks and networks should be defined and tested through analytical studies, optimization and/or simulation based assessments
- Efficiency: demonstration should be made that the proposed designs are increasingly more efficient and are ever more able to fulfill consumers expectations of faster, cheaper, convenient and reliable deliveries and returns, through analytical, optimization and / or simulation based assessments as well as pilot studies. This should be done at an individual smart locker bank level as well as at a network level
- Operating policy: Study of the impact of different operating policies on the efficiency of each design should be done through analytical, optimization and / or simulation based assessments
- Integration: the integration of such designs in a broader omnichannel business-to-consumer logistics and supply chain framework composed of different alternatives such as proposed [6] should be explored

The above challenges induce a set of research opportunities. Some of these are to focus on the design of one smart locker bank itself, with various level of Physical Internet concepts. When brought at a network level, there is also need for extending research

Table 2.1: Comparing Fixed and Modular Smart Locker Bank Designs

Design	Main advantages	Main disadvantages
Fixed	• Implementation cost • Economies of scale	• Adaptation to demand variability
Modular Towers	• Modular transportation / installation • Adaptation to global demand variations	• Adaptation to delivery patterns variations • Spare modules inventory • Capacity management
Modular Lockers	• Modular transportation / installation • Adaptation to global demand variations • Adaptation to delivery patterns variations	• Spare modules inventory • Capacity management
PI-Boxes as Mobile Modular Lockers	• Highly flexible configuration and capacity • High P/D efficiency	• Relies on emerging PI containers • Network wise capacity management • Technology challenges

on business models for the multi-operator use of hyperconnected pickup and delivery networks (e.g. [45]) as well as for predictive analytics for last-mile delivery patterns in the context of omnichannel business-to-consumer supply chains.

CHAPTER 3

SMART LOCKER BANK DESIGN OPTIMIZATION FOR URBAN OMNICHANNEL LOGISTICS: ASSESSING MONOLITHIC VS. MODULAR CONFIGURATIONS

This chapter examines two types of smart locker bank designs proposed in chapter 2: monolithic and modular configurations. Optimization-based layout design models are introduced for both configurations, and their relative performance is studied through numerical experiments. Results suggest that modular designs can perform just as well as custom fixed configuration designs while being more flexible and reconfigurable.
The work presented in this chapter has been published in *Computers & Industrial Engineering* under the following reference:

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3.1 Introduction

In the context of omnichannel business-to-consumer (B2C) logistics and supply chains, physical goods are delivered through a variety of channels to meet consumers preferences [46]. The consumer retail industry has dramatically changed, notably through the diversification of retail channels available since the digital world transformed retail business models [47]. Businesses operating within these channels aim to maximize their profit by analyzing each channels specificities [48]. [6] categorizes such delivery channels, including the emerging pick-at-locker (P@L). P@L is based on the large-scale exploitation of smart lockers as pickup and delivery (P/D) points, offering an intermediate solution

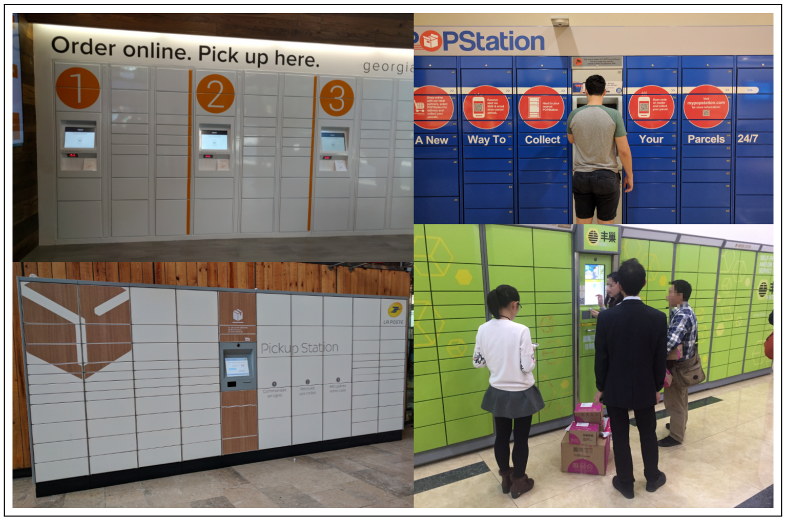


Figure 3.1: Examples of Fixed-Configuration Smart Locker Banks (source: photographs by authors)

between in-store pickup and home delivery. The P@L channel requires last-mile delivery capabilities, yet limited to visiting smart locker locations serving several consumers, thus avoiding individual home deliveries and minimizing travel for deliverers. Goods purchased by consumers are typically delivered to a smart locker bank conveniently located nearby the consumers home or workplace, thus mitigating risks of unsuccessful deliveries and the security implications of unattended delivery to the home as reported in [49]. In an urban environment, achieving this convenience requires implementing hundreds, even thousands, of smart locker banks across the urban agglomeration. [50] and [25] report the growth of such solutions in Europe, notably in the Netherlands, France, and Germany. Smart lockers are also fast growing in Asia, notably in China [51], and emerging in North America [52]. Figure 3.1 provides examples of smart locker banks used for B2C purposes.

Smart lockers are automated, provide secure storage for packages, and are potentially available 24/7 through smart authentication (e.g. using a government-issued ID or a smartphone). By deploying networks of smart locker banks, P@L has the potential of reducing delivery costs, city congestion, and greenhouse gas emissions, as reported in [26]. While the challenges of deploying and operating networks of smart locker banks have been studied through empirical and analytical modeling as well as through industry studies, little work has been published on the design of smart locker banks. The design problem is important because smart locker bank networks continue to be widely deployed in cities where prime real-estate is expensive and scarce. It is essential to identify methods to design efficient smart locker bank systems to induce high asset utilization and customer satisfaction.

This chapter addresses the design of smart locker banks for urban omnichannel logistics leveraging two conceptual designs proposed in [53] that are currently used in practice: (1) the fixed-configuration locker bank and (2) the modular tower based locker bank. The approach embraces a multi-stakeholder perspective and deals with uncertainty through a set of probabilistic scenarios. For logistic service providers delivering orders, it maximizes expected profit, by combining induced costs and revenues. For deliverers and customers, ergonomic costs are taken into consideration, depending on the dimensions and configuration of the smart locker bank itself. For both consumers and logistic service providers, minimum service levels are enforced, as service quality is of primary importance in the context of omnichannel B2C supply chains.

Design optimization models for both fixed-configuration locker bank and modular tower based locker bank configurations are developed. For fixed-configuration locker banks, optimizing the design involves deciding on (1) the global size of the bank (length and height), (2) the set of locker dimensions, (3) the number of lockers of each selected dimension, and (4) the layout of the lockers across the bank, as illustrated in Figure 3.2.

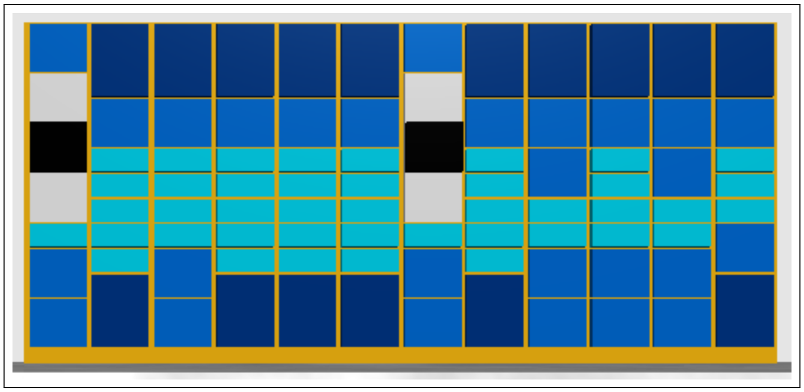


Figure 3.2: Illustration of Fixed-Configuration Smart Locker Bank Design Optimization (colors represent the different locker sizes)

The proposed optimization model for fixed-configuration smart locker bank design maximizes expected profits generated by serving a set of probabilistic delivery snapshot scenarios. Such scenarios are to be representative of delivery attempts (courier loading a set of parcels in lockers) at different points in time, with their respective probabilities representing uncertainty over future demand periods. Ergonomic costs and acquisition and implementation costs are modeled, as well as a restricted zone in which to implement the locker bank (e.g. an available space by the wall of a convenience store or in the ground floor hall of a high-rise building). Acquisition and implementation costs are to include maintenance due to material deterioration or theft attempts. The fixed-configuration locker bank design optimization model is adapted to three distinct contexts:

1. The design of each locker bank is customized for the location in which it is to be implemented.

2. A single design is to be used for all lockers in the urban agglomeration.

3. A limited set of designs is to be implemented, selecting among these the best fitting for each location.

Based on the alternative modular tower locker bank configuration, each locker bank within a territory (e.g. urban agglomeration, country) is designed to leverage a selected set of modular towers for the respective territory, as illustrated in Figure 3.3. Standard modular towers can be dynamically purchased, implemented and/or stored, allowing adapting the design of locker banks on a medium-term basis (e.g. monthly, quarterly or yearly). Having a limited number of modular tower designs potentially allows the reduction of acquisition and implementation costs through economies of scale.

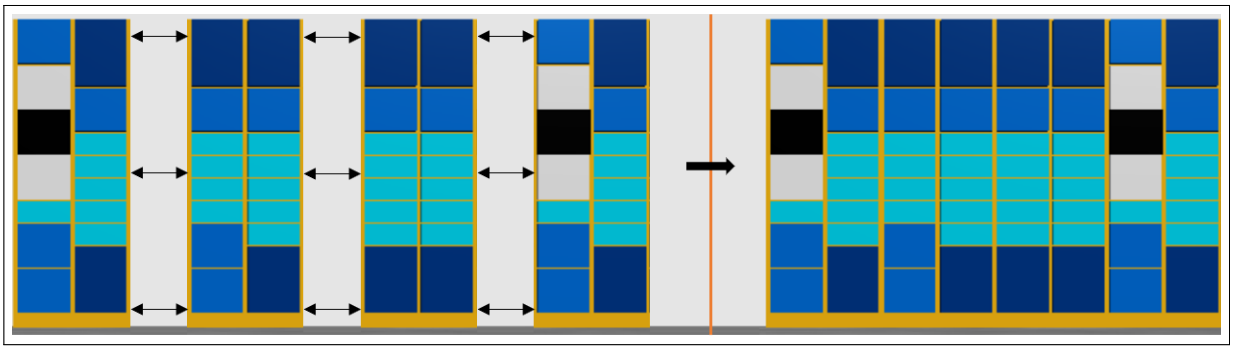


Figure 3.3: Illustration of Modular Towers Assembled into a Modular Tower Based Locker Bank Design (adapted from [53])

For this configuration, a set of modular towers is to be optimized for the territory, from which designs for specific locker banks are optimized by concatenating selected modular towers. The proposed optimization model for the design of modular tower locker banks has the same expected profit maximization objective as the fixed-configuration model, yet adapted to the dynamic modular-tower context, allowing to optimize specific modular tower locker bank designs.

The chapter contributes to the literature by introducing optimization based methods for designing smart locker banks leveraging two existing conceptual designs, providing empirical evidence of their performance, synthesizing strategic insights and drawing avenues for further research. The chapter scope does not include the design and operation of an entire network, rather, it focuses on a singular smart locker bank location.

The chapter is structured as follows. Section 3.2 presents the related literature, while positioning the chapter's contribution. Subsequent sections 3.3 and 3.4 respectively formally introduce the optimization modeling for fixed-configuration locker banks and modular-tower locker banks. Section 3.5 provides empirical results and analysis, with an emphasis on strategic insights. Finally, section 3.6 synthesizes the contributions of the chapter and discuss avenues for further research, notably further exploiting the concepts and principles of Physical Internet and Hyperconnected City Logistics introduced in [54].

3.2 Literature Review

This chapter proposes methods to design smart locker banks with a level of detail relevant to omnichannel supply chains that is not yet studied in the existing literature. In fact, research in this area is limited. However, there is extensive research on smart locker network deployment and operations, including industry studies. This section presents recent work on smart locker bank network deployment and operations, relevant work on the design of smart locker bank, and finally addresses related literature from other problem domains.

3.2.1 Smart Locker Bank Network Deployment and Operations Literature

[55] and [56] first introduced the use of "reception boxes" located outside homes for B2C deliveries of groceries, showing a logistics cost reduction between 40% and 60% compared to traditional home deliveries. The savings were mainly due to the extension of the delivery window enabled by unattended delivery. Yet, since the reception boxes were household specific, improvement could still be made using communal reception boxes [57]. [49] assessed the security implications of using communal reception boxes. The introduction of "smart tagging" was perceived as a way to overcome the security problems, thus creating the concept of smart locker banks.

Several papers have examined the development of smart locker bank networks in industry applications, assessing the solutions' efficiency [50, 58, 25, 59, 26, 60]. Sustainable networks in operation in Europe, notably in the Netherlands, Poland, France, and Germany are depicted. Smart lockers are also fast growing in Asia, notably in China [51], and emerging in North America [52]. Results show that smart locker banks enabled not only logistics cost savings, but also significant greenhouse gas emissions reduction due to improve delivery efficiency. The success of these existing networks is also attributed to the high coverage of the territory, ensuring convenient access to a pickup location. Convenient locations include main boulevards, shopping centers, commercial streets, locations suited to car access [61]. The problem of designing a smart locker bank network for B2C deliveries has been studied in [62] using an uncapacitated facility location model to find the optimal number, location, and sizes of smart locker banks so as to maximize profits.

3.2.2 Smart Locker Bank Design Literature

Literature on smart locker bank design for B2C supply chains was initiated in the logistics field by the European research project CityLog [63], where monolithic and modular smart locker bank concepts were introduced as a solution called the "Modular BentoBox System". The systen is part of an effort to improve the sustainability and efficiency of city logistics by decoupling the delivery of couriers from the customer pickup of parcels [64]. These design concepts were further developed in [53] who extended the monolithic versus modular conceptual dichotomy to differentiate four types of design: the fixed-configuration, the modular tower based, the modular locker based, and the Physical Internet handling container based smart locker banks. The focus in this chapter is on the fixed-configuration (monolithic) and the modular tower based (modular) smart locker designs. [65, 66] tackled monolithic locker bank configuration optimization, focusing on a case for internal use by hospitals for medical supply delivery. [65] proposed a genetic optimization algorithm to search for the optimal locker partition combination that allow a

maximal number of orders to be stored within the smallest space possible ensuring a minimum coverage of demand based on historical hospital supply delivery logs. While the method is relevant for the context of internal supply delivery in a hospital, the objectives (and therefore the resulting configurations) are different from the context of this chapter, focused on B2C supply chains. [66] compared basic and intuitive hill-climbing models, resulting with smart locker bank configurations partitioned with the same objective.
[67] recently proposed an ergonomics optimization approach to the design of monolithic smart locker banks, studying different locker sizes, and analyzing the standing vision range as well as the impact of height on user ergonomics in the context of B2C deliveries on a university campus. Human factors in industrial and logistic system design are very important [68] and have been studied in great depth for storage systems (e.g. [69]). [67] tackles this aspect in great depth. The approach taken in this chapter encompasses human factors, yet in a broader multi-stakeholder approach integrating consumer and deliverer centric ergonomic cost minimization with the logistic service provider profit maximization and consumer service satisfaction.

3.2.3 Related Literature

The problem of designing smart locker banks is related to the extensively studied two-dimensional and three-dimensional packing problems surveyed in [70] and [71]. These problems address the efficient packing of items in restricted spaces, fitting all items while minimizing wasted space. Efficient algorithms with complex objective functions have been studied for this problem (e.g. [72]). Smart locker bank design requires to choose a set of bins (lockers) for a variety of unknown items (potential deliveries), and to pack them into a restricted space. Moreover, the location of the lockers (e.g. height) have an impact on ergonomics and efficiency that is not reflected in packing problems. Therefore, adapting packing problems to the smart locker bank design problem would not entirely capture the essence of the problem.

Similarly, choosing a set of lockers to serve future demand (packages being delivered into the lockers) is related to inventory problems for equipment rental situations. Indeed, smart locker banks will face demand for empty lockers of a certain capacity (enough space to contain a parcel). Therefore, choosing the set of locker sizes composing a smart locker bank is similar to choosing a product portfolio and corresponding inventory to carry when running a rental business. This problem has been studied in several industries such as bike rental [73], car rental [74], or consumer goods rental [75]. However, these problems focus on inventory questions, and are not fit to model the physical complexity of designing a smart locker bank.

Finally, designing the configuration of a smart locker bank is related to the design of warehouse layout and warehousing storage racks such as in automated storage and retrieval systems (AS/RS). Warehouse problems are often concerned with the utilization of a storage system (i.e. a combination of racks, stacks, etc.). The problem is defined as the allocation of products to storage locations such as in [76] and [77]. AS/RS systems enable to store items in a very compact space retrieving them automatically with cranes or robots. However, such systems are meant to provide high storage capacity for standardized unit loads (e.g. totes) and the focus of the research in the field is on overall capacity and retrieval time estimation [78, 79]. Warehousing systems structure is not a primary point of focus as unit loads tend to be homogeneous. For example, a warehouse may deal with products at the level of standardized pallets or totes, which limits the variety of unit load shapes and sizes one has to deal with and makes the storage system structure less complex to design. The focus of this chapter is at the individual product scale (i.e. not like warehouses that deal with pallets of products) in an industry where unit loads are often not standardized (i.e. often custom packages). Therefore, while encompassing storage system utilization (the placement of packages in a specific locker), this chapter focuses on designing a storage system structure (the physical configuration of a smart locker bank).

3.3 Fixed-Configuration Locker Bank Design Optimization

3.3.1 Problem Statement

The proposed design optimization model for fixed-configuration locker banks maximizes a profit function composed of the expected revenues generated by serving a set of probabilistic delivery scenarios minus the associated ergonomic cost incurred by serving each order of each scenario (inbound and outbound handling ergonomic costs) and associated acquisition and implementation costs for the global dimensions of the bank and per locker implemented.

For illustrative purposes, three different modular sizes of locker are considered, multiples of the unit locker (1 x 1) as illustrated in Figure 3.4.

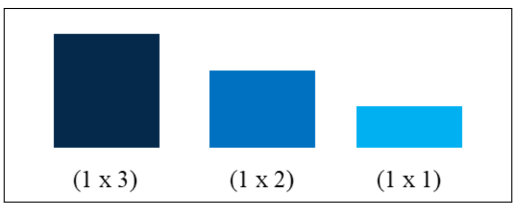


Figure 3.4: Illustration of three modular locker sizes; Large (L), medium (M) and small (S)

A smart locker bank is modeled as being composed of three elements: lockers, interactive modules, and facades. Provided the maximal dimensions of a smart locker bank location (e.g. horizontal and vertical dimensions of an available wall), the space is divided in grid units of the size of the unit locker as illustrated in Figure 3.5. Allocating lockers at different grid units creates a smart locker bank. For the purpose of avoiding holes in the structure of the bank, allocating a facade to conceal any locker-free grid unit within the limits of the smart locker bank is considered. While the nature of the structure of the bank is often rectangular, it may not be necessary to assign a locker at every grid unit, but an unconcealed space is not desirable to prevent structural complications or access to the interior of the bank. At the same time, a facade acts as a placeholder, and one can later replace it by a locker or other accessory if needed.

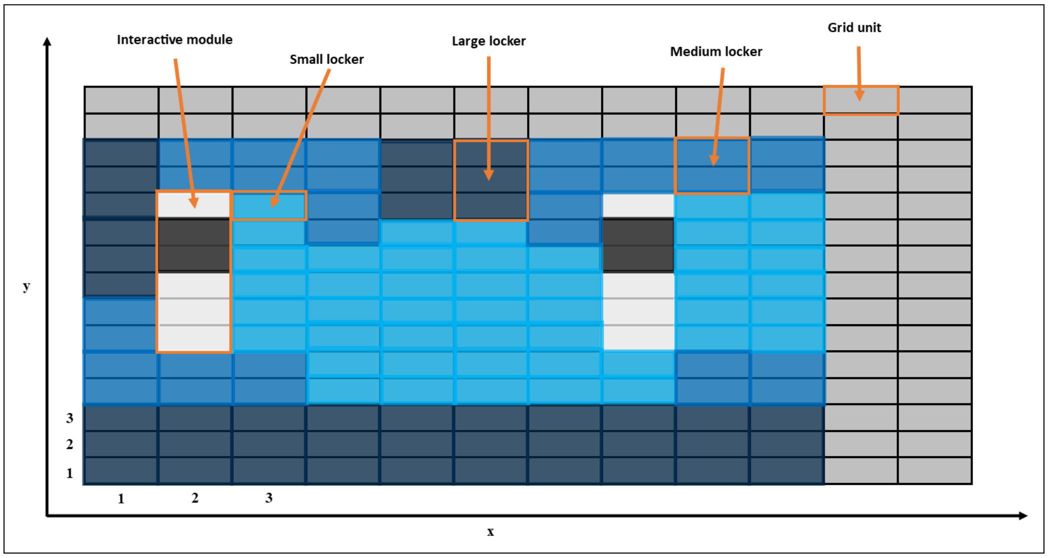


Figure 3.5: Illustration of a Smart Locker Bank and Its Design Grid

Figure 3.5 also illustrates a smart locker bank including two interactive modules (light gray rectangles with black insert). Such modules allow the use to interact with the bank through a computer terminal (e.g. for authentication), and has to be included in the design according to input parameters: number of interactive modules needed, and dimensions (1 x 6 in Figure 3.5). While currently an integral part of smart locker banks, future technological innovations may render the need for such interactive modules unnecessary. The proposed model is developed according to the following set of hypothesis:

- The dimensions of lockers and interactive modules are divisible in grid units. It is assumed that the size of a grid unit has been chosen accordingly.
- Only one unit of demand can be served per a locker in a scenario. This means that only one package at the time can be stored in an individual locker unit. For privacy

and anti-theft reasons, it is a reasonable assumption in the context of B2C logistics, as customers are to pickup their respective packages alone.

- Scenarios are representative of demand uncertainty and evolution over the considered planning period.
- Among all considered scenarios, the constructed smart locker bank must satisfy demand with a service level of at least α^G.
- For each individual scenario, the constructed smart locker bank must satisfy demand with a service level of at least α^L. This parameter is shared by all scenarios as it is meant to control the standard deviation of the service level under demand uncertainty.

3.3.2 Mathematical Model

Consider the set of grid unit locations $\mathcal{G}$ available to design a locker bank and the set of locker dimensions $\mathcal{D}$ considered for implementation in the design. In order to construct the locker bank design one needs to decide on the global dimensions (horizontal and vertical) of the bank and for each grid unit location $l \in \mathcal{G}$, one needs to decide whether:

- implement a locker of dimensions $d \in \mathcal{D}$
- implement an interactive module
- close the space with a facade
- keep the space empty, and leaving the entire row/column empty

Constructing such locker bank will generate amortized (with factor λ) acquisition and implementation costs c^L_d for each locker of dimension $d \in \mathcal{D}$, c^M for each interactive module, and $c^W W + 2c^S(W + H)$ for a bank with global dimensions W (width) by H

(height).

Then, for each demand scenario $s \in \mathcal{S}$ with respective probabilities p_s, demand for a locker of dimension d can be served by a locker of dimension $d' \in \mathcal{D}_d$ implemented in grid location l, generating a revenue of r_{ds} and an associated ergonomics cost $c^A_{dd'l} A_{dsd'l}$. Hereafter are introduced the indices, sets, input parameters and decision variables that formulate the overall model.

Indices

d	Locker or order dimension ($d \in \mathcal{D}$)
l	Grid unit location ($l \in \mathcal{G}$)
s	Scenario ($s \in \mathcal{S}$)
x	Column of grid units ($x = 1, ..., \bar{w}$)
y	Row of grid units ($y = 1, ..., \bar{h}$)

Sets

$\mathcal{D}$	Considered locker dimensions
$\mathcal{D}_d$	Locker dimensions in which a package of dimension d can fit ($\mathcal{D}_d \in \mathcal{D}$)
$\mathcal{G}$	Available grid unit locations
$\mathcal{G}_d$	Locations at which a locker of dimension d can have its lower left corner ($\mathcal{G}_d \in \mathcal{G}$)
$\mathcal{G}_{dl}$	Grid units covered by a locker of dimension d whose lower left corner is location l ($\mathcal{G}_{dl} \in \mathcal{G}$)
$\mathcal{G}^M$	Locations at which an interactive module can have its lower left corner ($\mathcal{G}^M \in \mathcal{G}$)
$\mathcal{G}^M_l$	Grid units covered by an interactive module whose lower left corner is location l ($\mathcal{G}^M_l \in \mathcal{G}$)

$\mathcal{S}$ Considered demand scenarios for the design

Input Parameters

α^G Minimum average service level

α^L Minimum service level for each individual scenario

$c^A_{dd'l}$ Ergonomic cost of assigning an order of dimension d in a locker of dimension d' located at l

c^M Cost of an interactive module

c^S Unitary bank surface cost

c^W Unitary bank width cost

d_{ds} Demand for a locker of dimension d in scenario s (expressed in number of packages)

d^T_s Total demand in scenario s; $d^T_s = \sum_{d \in \mathcal{D}} d_{ds}$(expressed in number of packages)

$\bar{h}$ Upper bound on the height of the bank

λ Amortization factor for acquisition and implementation costs over the considered period

$\underline{m}$ Minimum distance required between two consecutive interactive modules

n^M Number of locker columns an interactive module can cover

p_s probability of scenario s

r_{ds} Unit revenue yield by serving an order for dimension d in scenario s

$\bar{w}$ Upper bound on the width of the bank

Decision Variables

$A_{dsd'l}$ 0-1 Assignment of dimension d package in scenario s to a locker of dimension d' located at l

C_x 0-1 Use of grid unit column x in the locker bank design

F_l 0-1 Covering of grid unit location l with a facade

H Height of the locker bank (in grid units)

L_{dl} 0-1 Implementation of a locker of dimension d at location l

M_l 0-1 Implementation of an interactive module at grid unit location l

N_d Number of lockers of dimension d implemented in the design

R_y 0-1 Use of grid unit row y in the locker bank design

S_{ds} Number of orders of dimension d served in scenario s

W Width of the locker bank (in grid units)

3.3.3 Fixed-Configuration Locker Bank Design Problem (LBDP-FC)

The Fixed-Configuration Locker Bank Design Problem (LBDP-FC) can then be modeled as follows:

$$\max \sum_{s \in \mathcal{S}} p_s \Bigg(\sum_{d \in \mathcal{D}} r_{ds} S_{ds} - \sum_{d \in \mathcal{D}, d' \in \mathcal{D}_d, l \in \mathcal{G}_{d'}} c^A_{dd'l} A_{dsd'l} \Bigg) - \lambda \Bigg(\sum_{d \in \mathcal{D}} c^L_d N_d + \sum_{l \in \mathcal{G}^{\mathcal{M}}} c^M M_l + c^W W + 2c^S (W + H) \Bigg) \quad (3.1)$$

s.t.:

Constraints for the interactive module(s):

$$\sum_{l \in \mathcal{G}^M} M_l \geq \frac{W}{n^M} \quad (3.2)$$

$$M_l + \sum_{l' \in \mathcal{G}^M : l' \neq l, d(l,l') \leq \underline{m}} M_{l'} \leq 1 \qquad , \forall l \in \mathcal{G}^M \quad (3.3)$$

Assignment of lockers, facades, and interactive modules:

$$\sum_{dl' : l \in \mathcal{G}_{dl'}} L_{dl'} + F_l + \sum_{l' : l \in \mathcal{G}^M_{l'}} M'_l = Z_l \qquad , \forall l \in \mathcal{G} \quad (3.4)$$

$$N_d = \sum_{l \in \mathcal{G}_d} L_{dl} \qquad , \forall d \in \mathcal{D} \tag{3.5}$$

Constraints controlling binary variable Z_l:

$$Z_l \geq R_{y(l)} + C_{x(l)} - 1 \qquad , \forall l \in \mathcal{G} \tag{3.6}$$

$$Z_l \leq \frac{R_{y(l)} + C_{x(l)}}{2} \qquad , \forall l \in \mathcal{G} \tag{3.7}$$

Structural constraints:

$$xC_x \leq W \leq \bar{w} \qquad , \forall x \in \mathbb{N}, x \leq \bar{w} \tag{3.8}$$

$$yR_y \leq H \leq \bar{h} \qquad , \forall y \in \mathbb{N}, y \leq \bar{h} \tag{3.9}$$

Constraints for demand allocation to locker:

$$\sum_{d:d' \in \mathcal{D}_d} A_{dsd'l} \leq L_{d'l} \qquad , \forall s \in \mathcal{S}, \forall d' \in \mathcal{D}_d, \forall l \in \mathcal{G}_{d'} \tag{3.10}$$

Constraints for demand satisfaction integrity:

$$S_{ds} = \sum_{d'l:d' \in \mathcal{D}_d, l \in \mathcal{G}_{d'}} A_{dsd'l} \leq d_{ds} \qquad , \forall d \in \mathcal{D}, \forall s \in \mathcal{S} \tag{3.11}$$

Service level constraints:

$$\sum_{s \in \mathcal{S}} p_s \sum_{d \in \mathcal{D}} \frac{S_{ds}}{d_s^T} \geq \alpha^G \tag{3.12}$$

$$\sum_{d \in \mathcal{D}} \frac{S_{ds}}{d_s^T} \geq \alpha^L \qquad , \forall s \in \mathcal{S} \tag{3.13}$$

Maximizing the profit expression (3.1) corresponds to maximizing the sum, over the set of all probabilistic scenarios $\mathcal{S}$, of the revenues generated by serving each order of dimension d minus the incurred ergonomic cost, minus the amortized acquisition and implementation cost associated with implementing N_d lockers of dimension d, implementing interactive modules, and with the global dimensions of the bank. Note that the acquisition and implementation cost associated with the global dimensions of the bank represent an initial cost for building a structural basis, function of the width W of the bank, and a secondary cost accounting for materials use to build a skeleton of area $2(W + H)$ times the depth (assumed constant) of the bank. Expression (3.2) ensures that the total number of interactive modules implemented is sufficient to cover the width of the bank assuming a cover parameter n^M, while (3.3) ensures that each interactive module (if two or more) are distant from at least a minimum distance $\underline{m}$ for privacy purposes. $d(l, l')$ represents the horizontal distance between locations l and l'. Constraints (3.4) prevent the model from superposing lockers, facades or interactive modules at a same grid unit location, while also avoiding holes in the locker bank structure (empty grid unit). Holes are avoided by preventing the model from leaving a grid unit empty if an element has already been assigned in the same row/column through constraints (3.6) and (3.7). Expression (3.5) counts the number of lockers of each dimension d implemented, which is used in the objective function (3.1). Expressions (3.6) and (3.7) ensure that if a grid unit is used in the design, its corresponding column and row are also used, thus setting the global dimensions of the bank through constraints (3.8) and (3.9). For all scenarios considered by the model, each order is to be assigned to an available locker if the capacity of the smart locker bank allows it. Constraints (3.10) keep track of these assignment through the decision variables $A_{dsd'l}$, and make sure that they are consistent with the capacity of the bank, while constraints (3.11) ensure that the total number of orders assigned in each scenario is consistent with the demand. Taking a customer centric approach to the design of smart locker banks for omnichannel B2C supply chains, we aim to maintain a global minimum service level (average demand satisfaction ratio over all scenarios) by implementing constraint (3.12), and a lower bound α^G. Moreover, expression (3.13) also enforce a lower bound on local service levels to avoid large differences between scenarios.

3.4 Modular Tower Based Locker Bank Design Optimization

3.4.1 Problem Statement

The proposed optimization model for modular tower based locker bank design maximizes a profit function composed of the expected revenues generated by serving a set of probabilistic delivery snapshot scenarios minus the associated ergonomic cost incurred by serving each order of each scenario (inbound and outbound handling ergonomic costs) and associated implementation cost for each modular tower used. Three decisions are required to design a modular tower based locker bank, summarized into three questions:

- What is the horizontal global dimension of the bank?
- How many modular towers of each type is the bank composed of?
- How are the modular towers laid out?

In this chapter, a set of predesigned modular towers of width $w = 2$ inspired from field observations is considered (illustrated in Figure 3.6). Note that they both include interactive modules of same size as in the design of fixed-configuration smart locker banks.

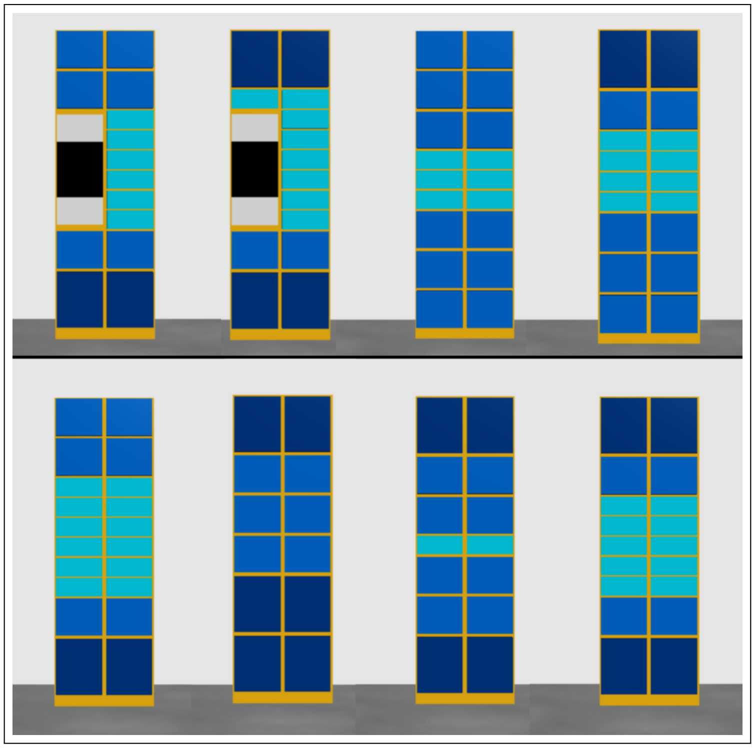


Figure 3.6: Illustration of Eight Modular Towers Considered for Designing Modular Tower Based Smart Locker Banks

The design of each individual modular tower is assumed to be ergonomically optimal for human interaction (inbound and outbound lifting efforts). This results in modular towers of predefined constant height (15 grid units in Figure 3.6). Now the space available to design a modular tower based smart locker bank can be divided in locations $j \in \mathcal{J}$ at which a modular tower can be implemented, as illustrated in Figure 3.7.

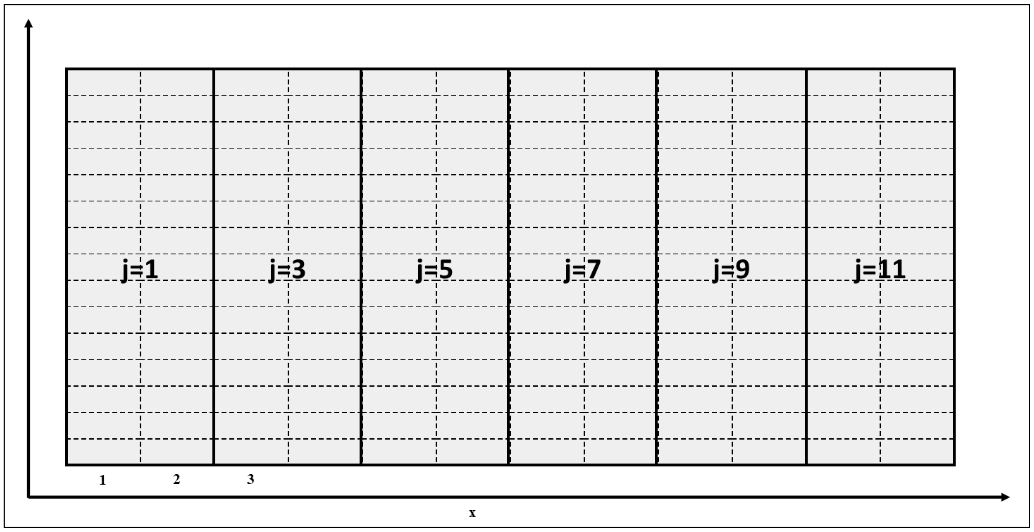


Figure 3.7: Illustration of a Modular Tower Based Smart Locker Bank Design Grid

3.4.2 Mathematical Model

Consider the set of grid unit locations $\mathcal{G}$ available to design a locker bank, the set of locations at which a modular tower can be implemented $\mathcal{J}$, and the set of modular tower types $\mathcal{I}$ considered for implementation in the design. To construct a locker bank design one needs to decide whether or not to implement a modular tower of type $i \in \mathcal{I}$ at location $j \in \mathcal{J}$. Constructing such locker bank will generate amortized (with factor λ) acquisition and implementation costs c^i for each modular tower of type $i \in \mathcal{I}$ implemented.
Then, for each scenario $s \in \mathcal{S}$, demand for a locker of dimension d can be served by a locker of dimension $d' \in \mathcal{D}_d$ implemented in grid location l if and only if a modular tower of type $i \in \mathcal{I}$ with a locker of dimension d' is located in modular tower location $j \in \mathcal{J}$ such that $l \in \mathcal{G}_j$ and $l \in \mathcal{L}^i$. It will generate a revenue of r_{ds} and an associated ergonomics cost $c^A_{dd'l} A_{dsd'l}$.

Hereafter are introduced supplementary indices, sets, input parameters and decision variables not previously defined in section 3.3.

Indices

i Modular tower type ($i \in \mathcal{I}$)

j modular tower location ($j \in \mathcal{J}$)

Sets

$\mathcal{G}_d$ Locations at which a locker of dimensions d has its lower left corner in at least one modular tower type

$\mathcal{G}^j$ Grid units locations covered by modular tower location j

$\mathcal{I}$ Modular tower types available

$\mathcal{J}$ Positions at which a modular tower can be implemented

$\mathcal{L}^i$ Potential locker assignment (d, l) in the overall grid for modular tower of type i

$\mathcal{M}$ Modular tower types i that are composed of an interactive module ($m^i = 1$)

Input Parameters

c^i Cost of acquiring and implementing a modular tower of type i

$\delta_{ii'}^{\underline{m}}$ Minimum distance between modular towers i and $i' \in \mathcal{M}$ satisfying $\underline{m}$ (depending on the locations of the interactive modules in types i and i')

λ Amortization factor for acquisition and implementation costs over the considered period

$\underline{m}$ Minimum distance required between two consecutive interactive modules

m^i 1 if modular tower i is composed of an interactive module; 0 otherwise

w Width of the considered modular tower in terms of grid units

Decision Variables

X_j^i 0-1 implementation of modular tower of type i at position j

3.4.3 Modular Tower Based Locker Bank Design Problem (LBDP-MT)

The Modular Tower Based Locker Bank Design Problem (LBDP-MT) can then be modeled as follows:

$$\max \sum_{s\in\mathcal{S}} p_s \Bigg(\sum_{d\in\mathcal{D}} r_{ds} S_{ds} - \sum_{d\in\mathcal{D}, d'\in\mathcal{D}_d, l\in\mathcal{G}_{d'}} c^A_{dd'l} A_{dsd'l} \Bigg) - \lambda \Bigg(\sum_{i\in\mathcal{I}} c^i \sum_{j\in\mathcal{J}} X_j^i \Bigg) \tag{3.14}$$

subject to:

Constraints for the interactive module(s):

$$\sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{J}} m^i X_j^i \geq \frac{W}{n^M} \tag{3.15}$$

$$X_j^i + \sum_{i'\in\mathcal{M}} \Bigg(\sum_{k\in J: j+w\leq k\leq j+\delta^m_{ii'}} X_k^{i'} \Bigg) \leq 1 \qquad ,\forall i\in\mathcal{M}, \forall j\in\mathcal{J} \tag{3.16}$$

Structural constraints:

$$\sum_{i\in\mathcal{I}} X_j^i \leq 1 \qquad ,\forall j\in\mathcal{J} \tag{3.17}$$

$$\sum_{i\in\mathcal{I}} X_j^i \geq \sum_{i\in\mathcal{I}} X_{j+w}^i \qquad ,\forall j\in\mathcal{J} : j+w\in\mathcal{J} \tag{3.18}$$

$$W = w \sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{J}} X_j^i \leq \bar{w} \tag{3.19}$$

Constraints for demand allocation to locker:

$$\sum_{d:d'\in\mathcal{D}_d} A_{dsd'l} \leq \sum_{i\in\mathcal{I}:(d',l)\in\mathcal{L}^i} X_j^i, j : l\in\mathcal{G}^j, \forall s\in\mathcal{S} \qquad ,\forall d'\in\mathcal{D}_d, \forall l\in\mathcal{G}_{d'} \tag{3.20}$$

Constraints for demand satisfaction integrity: 3.11

Service level constraints: 3.12, 3.13

Maximizing the profit expression (3.14) corresponds to maximizing the sum, over the set of all probabilistic scenarios $\mathcal{S}$, of the revenues generated by serving each order of dimension d minus the incurred ergonomic cost, minus the amortized acquisition and implementation cost of modular towers of type $i \in \mathcal{I}$ at location $j \in \mathcal{J}$. Expression (3.15) ensures that the total number of interactive modules implemented is sufficient to cover the width of the bank assuming a cover parameter n^M, while (3.16) ensures that modular towers composed of an interactive module (if two or more) are distant from at least a minimum distance m. Constraints (3.17) prevent the model from superposing modular towers at each location $j \in \mathcal{J}$. Expression (3.18) avoid holes in the locker bank. Expression (3.19) counts the number of modular towers of width w implemented to assess the global width W of the designed bank.

3.5 Experimental Results

The goal of the experiment is to compare the performance of each design optimization over sets of probabilistic scenarios. Exploring their sensitivity to different parameters, insights are identified, shaping recommendations and further research avenues.

3.5.1 Experimental Setting

The experiment considers four alternative locations. For each location, probabilistic scenarios are generated through Monte-Carlo simulation according to the following characteristics:

- The total number of packages per delivery snapshot follows a normal distribution of parameters (μ, σ)

- There are three sizes of packages according to a generated package mix ratio (% of small packages,
  % of medium packages, % of large packages)
- The package mixes are randomly generated from a target mix $(S\%, M\%, L\%)$ and can vary by ±5% around the target mix values (i.e. $(S\% \pm 5\%, M\% \pm 5\%, L\% \pm 5\%$, following triangular distributions, and globally normed to 100%)

For each location, fifty scenarios are randomly generated to ensure the stability of design decisions, each having a weight according to a uniform distribution subject to global norming to one. Each scenario at a location is built according to the parameters from table 3.1.

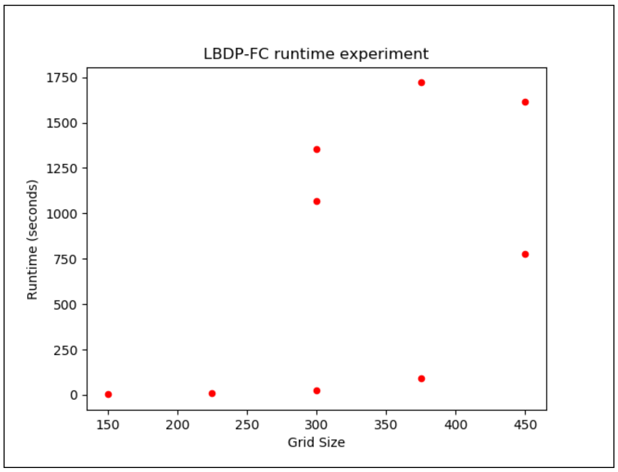
Table 3.1: Scenario Generation Parameters for Each Smart Locker Bank Location

Location	μ	σ	Average Package Mix
1	80	20	$(60, 25, 15)$
2	80	20	$(40, 20, 40)$
3	60	30	$(25, 50, 25)$
4	100	30	$(15, 25, 60)$

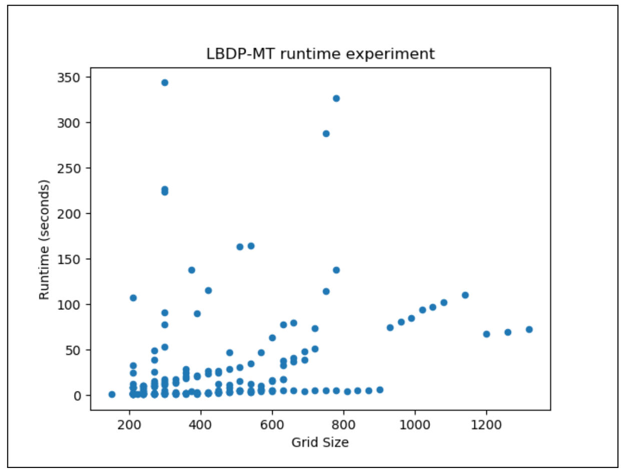
Unless stated otherwise, the input parameters used for the following experiments are indicated in A.

3.5.2 Solving Method

Both the LBDP-FC and LBDP-MT optimization models have been programmed with Python and the package Gurobipy, and solved with Gurobi 7 on a laptop computer with processor Intel(R) Core(TM) i7-6500U and 8GB of RAM. On a typical case, let say for the design of a smart locker bank for location 1 with default parameters, the LBDP-FC model has about 95k variables and 33k constraints. The LBDP-MT has a number of variables of the same order of magnitude (about 95k) but only about 900 constraints. The LBDP-MT, which has less configuration combinations to explore (concatenating modular towers), is therefore easier to solve. Figure 3.8 presents the optimization runtime in seconds for different grid sizes (number of grid units composing the design grid) representing all the experiments performed in this section.



(a) LBDP-FC: 9 experiments



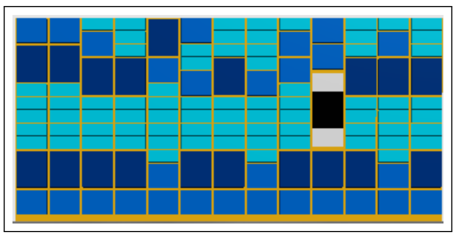
(b) LBDP-MT: 184 experiments

Figure 3.8: Experiments Runtime for the LBDP-FC and LBDP-MT Optimization Models

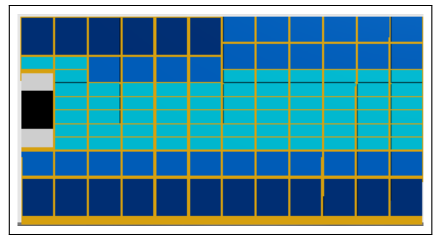
Although less experiments were needed for the LBDP-FC problem, Figure 3.8a shows that optimal solutions were found within 30 minutes (1800 seconds). Figure 3.8b confirms that the LBDP-MT model was easier to solve, with runtime never exceeding 350 seconds, even for larger grid sizes. These results are reasonable in the context of a design optimization at a tactical level, and emphasize the fact that this type of problem can be optimally solved in an efficient manner using available commercial software.

3.5.3 Contrasting the Optimized Designs

First let us look at the visual results of the proposed LBDP-FC and LBDP-MT optimization models over the four considered locations. Figures 3.9 to 3.12 illustrate visual results of optimal fixed-configuration and modular tower based smart locker bank designs side by side for each location indicating the value of the objective function (Obj), the revenues generated (Rev), the ergonomic cost (Erg), and the non-amortized acquisition and implementation cost (A&I) for each locker bank. Acquisition and implementation costs are presented non-amortized for an easier understanding of the range of costs involved by such designs.

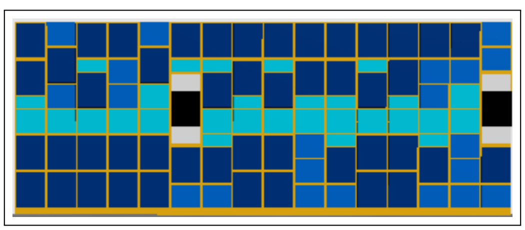


(a) Obj: 690.57, Rev: 781.7, Erg: 23.72, A&I: 8089

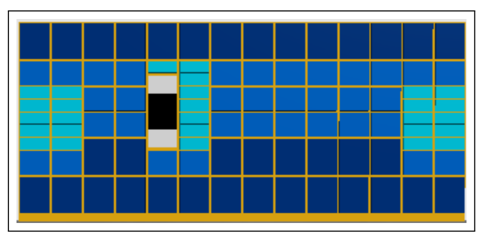


(b) Obj: 655.85, Rev: 777.54, Erg: 25.88, A&I: 11496

Figure 3.9: Design Optimization at Location 1: (a) Fixed-Configuration (b) Modular Tower Based

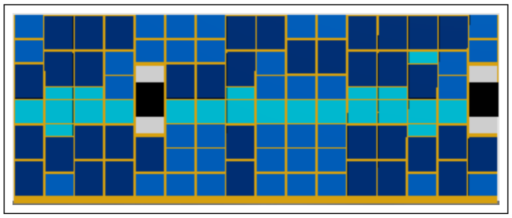


(a) Obj: 714.42, Rev: 813.93, Erg: 18.02, A&I: 9778

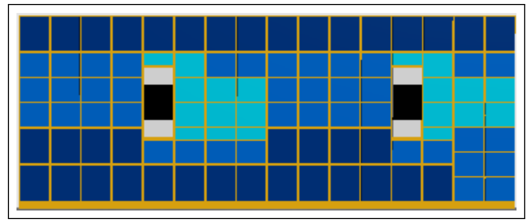


(b) Obj: 663.52, Rev: 796, Erg: 20.75, A&I: 13407

Figure 3.10: Design Optimization at Location 2: (a) Fixed-Configuration (b) Modular Tower Based

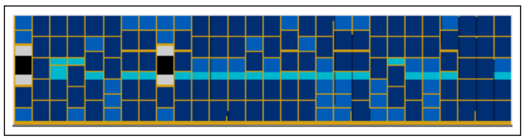


(a) Obj: 690.16, Rev: 789.84, Erg: 18.19, A&I: 9778

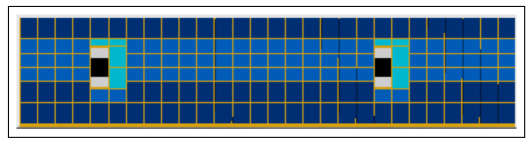


(b) Obj: 641.47, Rev: 789.08, Erg: 19.70, A&I: 15349.6

Figure 3.11: Design Optimization at Location 3: (a) Fixed-Configuration (b) Modular Tower Based



(a) Obj: 1173.81, Rev: 1338.93, Erg: 27.13, A&I: 16558



(b) Obj: 1048.85, Rev: 1299.90, Erg: 27.58, A&I: 26815

Figure 3.12: Design Optimization at Location 4: (a) Fixed-Configuration (b) Modular Tower Based

The visual outputs of the LBDP-FC (Fixed-Configuration) optimization model at the considered locations have a customized look: designs have very little similarities in terms of configuration. In contrast, the outputs of the LBDP-MT (Modular Tower based) optimization model have a more pleasant look, with lockers of different sizes gathered into clusters, making the smart locker bank look more streamlined. This occurs as look-and-feel is not considered in the proposed optimization models. While the LBDP-MT optimization model has more aesthetic appeal than the LBDP-FC optimization model, it is the only advantage compared with the components of the considered objective functions. Indeed, fixed-configuration designs result in higher profits, with both higher revenues, lower ergonomic cost, and lower acquisition and implementation cost.

3.5.4 Profit Function and Key Performance Indicators

This section presents the performance of the proposed LBDP-FC and LBDP-MT optimization models over the four considered locations, highlighting the contrast in terms of the objective profitability function, as well as service level and space utilization, two pertinent KPIs in the omnichannel B2C supply chain context. Table 3.2 presents objective function values, service levels, and space utilization for both fixed-configuration (LBDP-FC) and modular tower based (LBDP-MT) designs at each of the four considered smart locker bank locations. The service level is computed as the weighted average of service levels of the fifty scenarios for each location as in constraint (3.12). Space utilization is computed as the sum of accommodated package sizes divided by the sum of locker sizes composing the bank. Space utilization is the weighted average of each space utilization ratio for each scenario.

Table 3.2: Performance of the Two Proposed Design Methods over the Four Locations: KPIs

Location	Model	Objective Value	Service Level	Space Utilization
1	LBDP-FC	690.57	99.97%	68.32%
	LBDP-MT	655.85	99.45%	73.63%
2	LBDP-FC	714.42	99.67%	59.65%
	LBDP-MT	663.52	98.43%	66.63%
3	LBDP-FC	690.16	99.68%	57.38%
	LBDP-MT	641.47	99.56%	57.33%
4	LBDP-FC	1173.81	99.92%	56.98%
	LBDP-MT	1048.85	98.45%	55.27%

In Table 3.2, modular tower based locker bank designs yields a lower objective function value at all four locations, with gaps of respectively 5%, 7.12%, 7.05% and 10.65%.

However, it is interesting to note that both models yield similar service levels at all four locations. For space utilization, the LBDP-MT optimization model yields the best ratio for location 1 and 2, and similar ratios for location 3 and 4.
While the acquisition and implementation cost is specific to the considered smart locker bank, the components ”revenues - ergonomic cost” are specific to the considered scenarios and can be explored in more detail. Figure 3.13 compares the (revenues - ergonomic cost) generated by the LBDP-FC and LBDP-MT optimization models, comparing each by plotting distributions over the sets of fifty scenarios in box-and-whisker diagrams for each location and type of locker design.

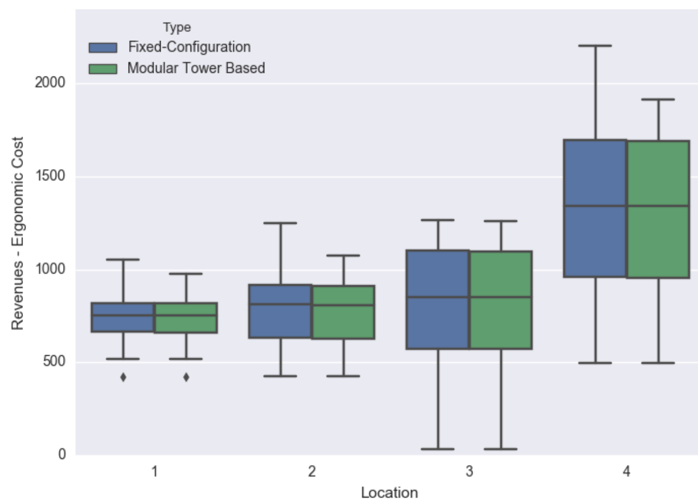


Figure 3.13: Performance of the Two Proposed Design Methods over the Four Locations: Objective Value

These box-and-whisker (Tukey box plot) diagrams graphically depict groups of numerical data through their quartiles. Thus, one can observe that the first, second and third quartiles for both models have very similar performance. The difference lies in the spread of the distributions, especially for locations 1, 2, and 4, where it can observe that the fixed-configuration design model yields higher results.

The performance of the LBDP-MT optimization model in these illustrative examples is close to the LBDP-FC optimization model, although the acquisition and implementation cost component seem to be the origin of the difference in objective profitability function values.

3.5.5 Sensitivity Analysis on Acquisition and Implementation Costs

The authors argue that using modular tower based locker bank designs offer opportunities of acquisition and implementation (A&I) cost savings enabled by economies of scale. It is reasonable to assume that the cost of a modular tower can be driven lower than the cost of a fixed-configuration locker bank of similar configuration. However, because of the structure of the costs in (3.1), it can be expected that for a certain length of smart locker bank, a modular tower based design will eventually become more expensive than a fixed-configuration design as more modular towers are added. This happens because a modular tower has a structure supporting the individual tower, while the fixed-configuration design structure supports the entire bank, reducing the cost per column of lockers. Figure 3.14 illustrates this concept.

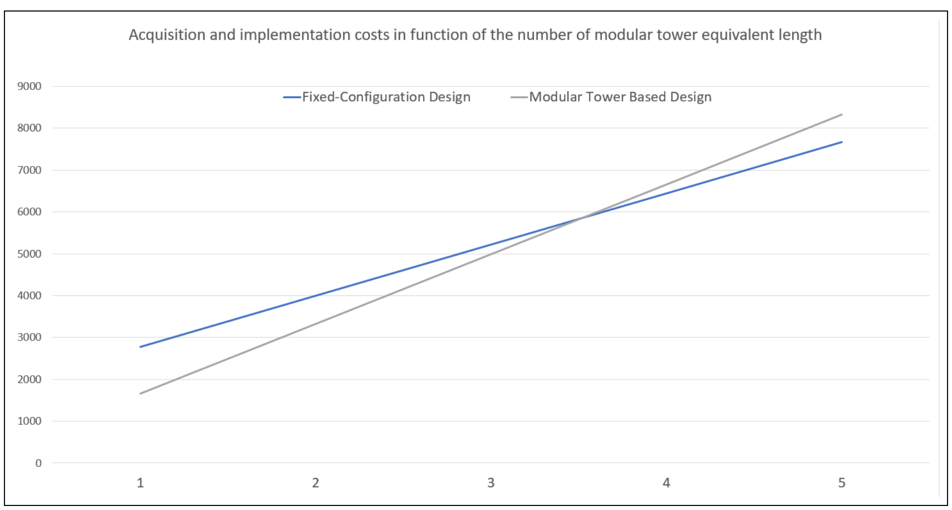


Figure 3.14: Acquisition and Implementation Costs of a Modular Tower Based Design vs. Fixed-Configuration Design

This section explores the impact of the relative cost of a modular tower on the performance of the modular tower based design optimization model. Focusing on location 1, the model is solved with the cost of an individual modular tower being 50%, 70%, 85%, 100% and 120% (c^i (%)) of the cost of acquiring and implementing a fixed-configuration bank of similar configuration. Table 3.3 summarizes the results of the experiment, presenting the objective values, generated revenues, ergonomic costs, and non-amortized acquisition and implementation costs of the optimal solutions found for both LBDP-FC and LBDP-MT optimization models.

Table 3.3: Sensitivity Analysis on Acquisition and Implementation Costs at Location 1

Model	c^i (%)	Objective Value	Revenues	Ergonomic Cost	A&I Cost
LBDP-FC	-	690.57	781.71	23.72	8089.0
LBDP-MT	50%	683.22	777.54	25.89	8212.0
	70%	655.85	777.54	25.88	11496.8
	85%	635.32	777.54	25.88	13960.4
	100%	614.79	777.54	25.88	16424.0
	120%	587.42	777.54	25.88	19708.8

The results show the variation of the cost of individual modular tower impacts mostly the acquisition and implementation cost of the resulting smart locker bank. There is almost no change in the revenues or ergonomic costs. One can also note that the performance of the modular tower based design model yields a bank with performance similar to the fixed-configuration design model with an individual modular tower cost of 50% the value of its equivalent fixed-configuration smart locker bank (objective value within 1%). However, when the ratio is increased to 120%, the performance drop is within 15% (and the cost of the modular tower based bank more than doubles the fixed-configuration bank). This experiment is helpful to understand that the cost of individual modular towers may have a consequent impact on the performance of the modular tower based locker bank design optimization model, at least at the location level. Indeed, when designing a whole network of smart locker banks, the advantages of the modular tower based design become apparent as a large number of the same modular towers can be bought together, potentially enabling highly significant discounts, when the fixed-configuration design is customized for a specific location.

3.5.6 Importance of Modular Tower Availability

The modular tower based locker bank designs assumes that a set of predesigned modular towers is available for selection. The optimization model then just need to select and concatenate the best set of modular towers available to build a smart locker bank. This section explores the impact of the available types of modular towers by iteratively removing the most used (greatest impact on the structure of designed banks) type from the set of available modular towers. Note that to ensure feasibility, constraints (3.19) are iteratively relaxed. That is, if the model is infeasible, or if the solution found has width $W = \bar{w}$, $\bar{w}$ is increased by two units, and the model is solved again. Table 3.4 presents the iterations performed, and the resulting modular tower based locker bank configurations (modular tower type and number), as well as the objective values, service levels (SL), and space utilization ratio (SU). Next removals are identified in bold.

Table 3.4: Iterations of Modular Tower Availability and Resulting Smart Locker Banks (Next Removal in Bold)

Availability	Location	Composition (type(number))	Bank width	Objective	SL	SU
$\lvert I \rvert = 8$	1	2(1) - 5(3) - 8(2)	12	655.85	99.45%	73.63%
	2	2(1) - **6(4)** - 8(2)	14	663.52	98.43%	66.63%
	3	2(2) - 4(1) - **6(4)** - 8(1)	16	641.47	99.56%	57.33%
	4	2(2) - **6(12)**	28	1048.85	98.45%	55.27%
$\lvert I \rvert = 7$	1	2(1) - 5(3) - **8(2)**	12	655.85	99.45%	73.63%
	2	2(2) - **8(6)**	16	638.31	98.14%	57.51%
	3	2(2) - 7(4) - **8(2)**	16	630.67	99.10%	56.50%
	4	2(3) - 7(2) - **8(15)**	40	954.34	98.45%	38.69%
$\lvert I \rvert = 6$	1	2(1) - 5(4) - **7(1)**	12	652.33	99.26%	73.31%
	2	2(2) - **7(6)**	16	636.88	98.14%	57.51%
	3	2(2) - **7(6)**	16	629.76	99.01%	56.47%
	4	2(3) - **7(17)**	40	953.09	98.45%	38.69%
$\lvert I \rvert = 5$	1	2(2) - **5(4)**	12	650.79	99.26%	73.31%
	2	2(4) - **5(9)**	26	573.95	98.67%	35.78%
	3	2(3) - 4(2) - **5(4)**	18	575.45	96.52%	47.3%
	4	2(7) - **5(18)**	50	811.90	95.41%	29.21%
$\lvert I \rvert = 4$	1	2(2) - 4(4)	12	646.07	98.73%	73.01%
	2	2(3) - 4(8)	22	561.73	96.40%	40.43%
	3	2(3) - 4(6)	18	572.37	96.56%	47.35%
	4	2(7) - 4(18)	50	790.41	95.41%	29.21%

First it can be observed that in order to maintain the enforced service levels, smart locker bank widths at certain location dramatically increase; for example, from the beginning to the end of the experiment, location 4's bank width increases from 28 to 50 grid units. This clearly shows that the remaining modular tower types are not a good fit for location 4's demand, and its space utilization ratio can be expected to drop as availability is decreasing. However, at location 1, the bank width is steady along all iterations of the experiment, indicating that the availability of modular tower types has little effect, and that there is always a combination of modular tower types that fit location 1's demand in the scope of this experiment (stopping at $|I| = 4$); its space utilization ratio can be expected to be almost steady against the decrease in modular tower type availability. Indeed, location 1's performance is not substantially impacted by the decrease in modular tower type availability; its objective value drops by 1.5% between the beginning and the end of the experiment. In contrast, location 4 is dramatically impacted, and its objective value drops by almost 25%, which mostly comes from the acquisition and implementation cost increase due to the width of the bank almost doubling. Moreover, its service level decreases only by a little, while its space utilization drops from 55.27% to 29.21%. This experiment highlights the importance of the available types of modular towers for the LBDP-MT optimization model, emphasizing the need to be carefully designed to fit multiple smart locker bank locations to benefit from economies of scale. It is even more important as having a large number of modular tower types is potentially harder to manage.

3.5.7 Space Restrictions

Until now, the width of available space (and resulting grid) was never a constraint for both models; resulting smart locker banks for all experiments are not using the full grid available. As a result, for location 4, solutions have widths that could be seen as excessive (28 grid units in section 3.5.3). This last experiment explores the impact of space restrictions at location 4 by incrementally decreasing $\bar{w}$, relaxing the service level constraints (3.12) and (3.13) to ensure feasibility. Table 3.5 summarizes the results of the experiment, presenting the objective values, service levels, and space utilization ratio of the optimal solutions found for both LBDP-FC and LBDP-MT optimization models.

Table 3.5: Performance of the Models Against Space Restrictions

$\bar{w}$	Model	Objective Value	Service Level	Space Utilization
30	LBDP-FC	1173.81	99.92 %	56.98 %
	LBDP-MT	1048.85	98.45 %	55.27 %
25	LBDP-FC	1167.80	99.02 %	62.96 %
	LBDP-MT	1028.31	96.29 %	61.89 %
20	LBDP-FC	1103.92	94.79 %	73.56 %
	LBDP-MT	985.99	92.90 %	69.82 %
15	LBDP-FC	959.95	85.01 %	84.67 %
	LBDP-MT	851.98	82.02 %	83.93 %
10	LBDP-FC	716.63	66.58 %	94.45 %
	LBDP-MT	662.33	65.99 %	90.34 %

SWith limited space,less demand can be fulfilled, resulting in the objective value decreasing along with service level. Despite this, however, space utilization increases faster than the decrease of objective value and service level, as more combinations of demand to serve are available as the space is more restricted. It makes it easier to find perfect matches between packages and lockers, thus limiting lost space.

3.6 Conclusion

Smart locker networks are promising contributors toward solving the last-mile delivery problem brought by a global urbanization of the world's population, and the challenges of e-commerce and omnichannel B2C supply chains. They can be beneficial to cities, in reducing logistic flows by taking advantage of consolidation opportunities; to logistic carriers, reducing the number of failed deliveries and reducing the number of vehicles and deliverers needed to cover a geographic area; to omnichannel retailers, by diversifying the service offerings; and finally to urban citizens, by offering convenient pickup and delivery locations.

This chapter contributes to the development of last-mile delivery solutions and complements the smart locker bank network design literature by proposing an optimization based methodology for designing monolithic and modular smart locker banks in the context of omnichannel B2C logistics, and demonstrating that modular designs can perform just as well as fixed-configuration designs while being more flexible.

Optimization models are proposed for two of the smart locker bank designs proposed in [53]: the fixed-configuration locker bank and the modular tower based locker bank. The models generate smart locker banks design maximizing profit leveraged by omnichannel supply chains, considering acquisition and implementation components as well as deliverer and consumers physical interactions with lockers (ergonomic efforts).

The authors report on experiments demonstrating that the modular tower based locker banks can perform closely to the fixed-configuration locker banks. The use of modular towers can be an advantage when deploying networks of smart locker banks, assuming one manages to take advantage of economies of scale to produce modular towers cost effectively. The experiments also showed that the set of modular towers available can dramatically impact the performance of a smart locker bank, thus highlighting the importance of well-designing sets of modular towers. Lastly, when the space is limited, the performance of both models drops rapidly, which can be a constraint when deploying a network over a highly priced real estate market, for instance.

Table 3.6 synthesizes strategic insights highlighted in the chapter. From a managerial perspective, modular tower based smart locker banks have the advantage of being more flexible in a market where demand evolves over time. Fixed-configuration designs may be cheaper to implement as they require a one-time implementation of the smart locker bank. However, their monolithic structure may also require special equipment (e.g. truck, handling) for transportation and installation which induces some additional cost. A main disadvantage of fixed-configuration designs is the lack of flexibility regarding demand evolution. The modular tower based design allows expansion and reduction of capacity of a location as time passes, following demand patterns and trends. As suggested in [80], the overall network's capacity can be dynamically managed, relocating, increasing, or decreasing the number of modular towers deployed (at the cost of dealing with dynamic capacity management). This also requires the careful design of modular towers, and may also require holding a certain amount of modular towers in inventory to avoid delay when the network's capacity needs to be increased. With fixed-configuration, as demand changes, there are three choices: (1) add an adjacent locker bank; (2) replace the current locker bank by a better adapted one, and try to find a better fitting place for the displaced one, sell it or discard it; (3) keep it as it is, reducing service quality as clients will have to rely on other banks or channels.

Table 3.6: Comparing Fixed and Modular Smart Locker Bank Designs (adapted from [53])

Design	Main advantages	Main disadvantages
Fixed	• Implementation cost • Economies of scale	• Transportation and installation equipment • Adaptation to demand evolution
Modular	• Transportation and installation • Adaptation to demand evolution	• Capacity management • Modular tower design and inventory

Finally, there are numerous opportunities for further smart locker research and innovation. The dynamic optimization of the set of modular towers to be used across a locker bank network is a natural extension of this chapter. The exploitation of modular lockers and modular containers, introduced in [53] also opens a rich terrain for research on design and operation of such modular lockers, containers and banks, within a rich conceptual framework for Physical Internet enabled hyperconnected omnichannel urban logistics and supply chains. There is significant need for research investigating the relative performance of an overall network of smart locker banks under various set of bank design options in omnichannel B2C environment. Finally, similar research is needed relative to smart logistic locker banks, not designed for consumer access, but rather for exploitation as distributed access hubs for couriers and logistics service providers, notably in hyperconnected urban parcel logistics networks (e.g. [81]).

CHAPTER 4
DYNAMIC POOLED CAPACITY DEPLOYMENT FOR URBAN CAPILLARY LOGISTICS NETWORKS

This chapter focuses on a novel tactical problem: the dynamic deployment of pooled access hub capacity modules in an urban parcel network operating under space-time uncertainty leveraging modular capacity relocation inspired by chapter 3. In particular, it proposes a two-stage stochastic optimization model for the access hub dynamic pooled capacity deployment problem with synchronization of underlying operations through travel time estimates, and a solution approach based on a rolling horizon algorithm with lookahead and a benders decomposition able to solve large scale instances of a real-sized megacity. Numerical results, inspired by the case of a large parcel express carrier, are provided to evaluate the computational performance of the proposed approach and suggest up to 28% last-mile cost savings and 26% access hub capacity savings compared to a static capacity deployment strategy.

The work presented in this chapter has been submitted for publication in a peer-reviewed journal; the preprint version is available under the following reference:

- L. Faugère, W. Klibi, C. White III, and B. Montreuil, ”Dynamic Pooled Capacity Deployment for Urban Parcel Logistics”, *arXiv:2007.11270 [cs, math]*, Jul. 2020, arXiv:2007.11270, 2020.

4.1 Introduction

Global urbanization, growth of e-commerce and the ever increasing desire for speed put pressure on the need for innovation in designing, managing and operating urban logistics systems in a sustainable and cost-efficient way. In 2018, 55% of the world's population lived in urban areas (up to 82% in North America). The [37] predict that global urbanization will reach 68% by 2050, with an increasing number of megacities (cities of 10+M inhabitants). Increasing population density is a challenge for city logistics in terms of traffic congestion, vehicle type restrictions, limited parking spaces, expensive and rare logistic facility locations, and is further complex in megacities due to their extremely high density [82]. For urban parcel logistics systems, the growth of e-commerce is currently one of the main challenges to tackle with an annual growth over 20% on the 2017-2019 period, projected to be over 15% until 2023 [83]. Online-retailing with goods being transported to consumers' homes increase the number of freight movements within cities while reducing the size of each shipment [5] which makes first and last mile logistic activities harder to plan. Moreover, consumers' desire for speed (i.e. same-day delivery and faster) has yet to be met by online retailers [84]. With promises as fast as 1-hour delivery (e.g. Amazon Prime in select U.S cities), the cost of last-mile logistics becomes an ever more critical part of urban parcel logistics. These trends have been accelerated due to attempts to mitigate the impacts of the COVID-19 pandemic (e.g., sequestering in place), requiring companies to increase their last-mile delivery capabilities and to deal with the dramatic shift to online channels [85].

To tackle these challenges, a number of innovations have emerged from academia and industry. [5] provide an overall view of recent innovations and modeling of solutions such as multi-echelon networks, dynamic delivery systems, pickup and delivery point networks, omni-channel logistics, crowd-sourced transportation and the integration of public and freight transportation networks. Many of these innovations are considered in the Physical Internet initiative, introduced in [3], which seeks global logistics efficiency and sustainability by transforming the way physical objects are handled, moved, and stored by applying concepts from internet data transfer to real-world shipping processes.

A conceptual framework on the application of Physical Internet concepts to city logistics was recently proposed in [4], in particular the concepts of pooling and hyperconnectivity in urban multi-echelon networks. As underlined by [5], city logistics problems integrating real-life features such as highly dynamic and volatile decision making environments, sharing principles or multi-echelon networks, offer a fertile soil for groundbreaking research.

Inspired by the case of a large parcel logistics company operating in megacities, this chapter examines a novel tactical optimization problem in urban parcel logistics. It consists in the dynamic deployment and relocation of pooled storage capacity in an urban parcel network operating under space-time uncertainty. It builds on the recent proposal of a hyperconnected urban logistics network structure [81] in line with the new challenges of the parcel logistics industry. The proposed network structure is based on the pixelization of urban agglomerations in unit zones (clusters of customer locations), local cells (cluster of unit zones) and urban areas (cluster of local cells). It is composed of three tiers of interconnected logistics hubs: gateway hubs (GH), local hubs (LH) and access hubs (AH) respectively designed to efficiently handle inter urban areas, inter local cells, and inter unit zones parcel flows. Beyond the realm of an urban agglomeration, the network of gateway hubs connects to a network of regional hubs (RH) covering entire blocks of the world (e.g. North America), and these regional hubs connect to a worldwide network of global hubs. This chapter focuses on access hubs which are small logistics hubs located at the neighborhood level within minutes of customers, enabling parcel transfer between different vehicle types temporarily holding parcels close to pickup and delivery points. Access hubs are to be used by logistics carriers, and not by consumers as smart lockers are. Access hubs can materialize in many forms including a parked trailer, a smart locker bank, or a storage shed as illustrated in Figure 4.1. Trailer based solutions like Figure 4.1 (a) and (d) offer all-or-nothing mobile solutions, while capacity module based solutions like Figure 4.1 (b) and (c) offer flexible capacity adjustment over time. The scope of this chapter is a capacity module based solution.

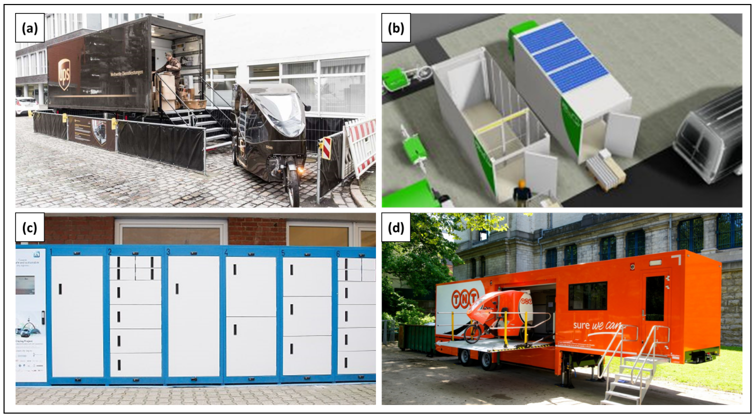


Figure 4.1: Examples of Access Hubs: (a) Trailer Micro-hub in Berlin by [86], (b) Storage Shed by [87], (c) Transshipment Locker Bank by [88], and (d) Trailer by [89]

Parcel logistics networks have undergone significant changes in the last 20 years, notably in urban contexts as seen in [90], and have received an increasing attention in the academic literature. Strategic and tactical network design problems such as the ones examined by [91, 92] approximate operations costs when designing and planning for multi-echelon networks. While network design problems are complex due to intricate interdependencies between strategic, tactical and operational decisions, continuum approximations (see [93]) are useful to capture operations complexity and take informed decisions. However, such approximations are typically used to estimate travel distance and cost, but not travel time and operations synchronization. This chapter considers access hubs to be modular in storage capacity similar to designs proposed in [94], such that capacity modules can be removed/added to adapt access hub's storage capacity. At the tactical level, capacity modules are to be deployed over a network of access hub locations; at the operational level, capacity modules are to be allocated to serve their access hub's need or neighboring locations via capacity pooling. In a dynamic setting, the associated problem can be related to a multi-period location-allocation problem which belongs to the NP-

Hard complexity class [95]. Once the capacity of the network of access hubs is adjusted, each access hub plays the role of a transshipment location between couriers performing pickup and delivery services within minutes of the access hub and riders transporting parcels between local hubs and a set of access hubs. Such transshipments require tight synchronization of the two tiers so as to provide efficient and timely pickup and delivery operations. This operational context mimics, on a hourly basis, a two-echelon pickup and delivery problem with synchronisation, which is a complex routing problem (see for instance [96]). Thus, the integration of operations in the tactical decision model leads to better capacity deployment decisions [97], yet induces solvability challenges due to its combinatorial and stochastic-dynamic structure.

This chapter studies a novel tactical optimization problem: the dynamic deployment of pooled storage capacity in an urban parcel network operating under space-time uncertainty where tactical decisions encompass the relocation of capacity modules over a set of discrete locations and recourse capacity pooling decisions are controlled at the operational level. Its contribution is threefold: (1) the characterization of a new tactical problem for capacity deployment, motivated by dynamic aspects of urban parcel logistics needs, (2) the modeling of the access hub dynamic pooled capacity deployment problem as a two-stage stochastic program with synchronization of underlying operations through travel time estimates, and (3) the design of a solution approach based on a rolling horizon algorithm with lookahead and a benders decomposition able to solve large scale instances of a real-sized megacity. Numerical results, inspired by the case of a large parcel express carrier, are provided to evaluate the computational performance of the proposed approach and suggest up to 28% last-mile cost savings and 26% capacity savings compared to a static capacity deployment strategy.

Section 4.2 summarizes the literature relevant to this type of problem, section 4.3 describes the problem and proposes a mathematical modeling, section 4.4 presents the proposed solution approach, section 4.5 provides an experiment setup and discusses results, and section 4.6 highlights key takeaways and managerial insights, and identifies promising research avenues.

4.2 Literature Review

Multi-echelon network for urban distribution have received a lot of attention in the academic literature (e.g. [30], [98], [99]), commonly using urban consolidation centers (UCC) to bundle goods outside the boundaries of urban areas. As reported in [29], several micro-consolidation initiatives have been proposed to downscale the consolidation effort by bundling goods at the neighborhood level using capillary networks of hubs located much closer to pickup and delivery points, defined as access hubs in the conceptual framework proposed by [81]. Examples of such initiatives are satellite platforms (e.g. [30]), micro-consolidation centers (e.g. [31]), mobile depots (e.g. [32]), and micro-depots [33]. Most of the focus has been on location and vehicle routing aspects (e.g. [100] and [101]) and cost and negative externalities assessment (e.g. [35], [102], [32]) in solutions using depots and cargo-bikes. To the best of the authors' knowledge, the dynamic management of access hub capacity for urban parcel logistics has not yet been studied in the academic literature. The problem studied in this chapter involves modular capacity relocation and a capacity pooling recourse mechanism impacting the operations of a two-echelon synchronization problem. In this section, a literature review on dynamic capacitated facility location problems and integrated urban network design problems is presented.

Dynamic facility location problems where systems are subject to varying environments (e.g. non-stationary demand) allow the relocation of facilities over time. [103] provide a literature review on facility location dynamics, including problems with and without hub relocation. Innovations in the manufacturing industry have motivated the study of modular and mobile production and storage. [104] have presented various threads of innovations such as distributed production, on-demand production, additive production, and mobile production, that would motivate and benefit from hyperconnected mobile production systems. [105] and [106] proposed mathematical modeling for production and inventory capacity relocation and allocation to manage multi-facility network facing stochastic demand. However, they examine small to medium networks far from the scale of urban parcel logistics networks and do not study operations synchronization. [107] studied storage capacity expansion planning coupled to dynamic inventory relocation in the context of warehouse location allocation problems, but did not consider capacity reduction or relocation. [108], [109], and [110] modeled dynamic facility location problem where not only sites could be permanently or temporarily opened or closed, but also resized by adding or removing modular capacity. [109] proposed models capturing modular capacity shifts from existing to new facilities. However in these problems, capacity relocation is generally not managed jointly with capacity allocation or its impact on underlying operations. Dynamic facility location literature partially covers the tactical capacity relocation problem studied in this chapter, but does not integrate underlying operations dynamics at the urban logistics scale.

Integrated network design problems typically deal with a combination of strategic decisions such as facility location, tactical decisions such as resource allocation and scheduling, and operational decision such as vehicle routing. The integration of these different levels of decisions can be found in two main problem classes: service network design problems and location routing problems. Service network design problems deal with the selection and scheduling of services such as hub operations, shipping lines and routing of freight (e.g. [111, 112]) while location routing problems combine facility location-allocation decisions with associated freight routing decisions. [113] provide a recent survey of variants and extensions of the location routing problem. The dynamic location routing problem ([114]) considering the assignment of demand to locations over multiple periods, is similar to the problem studied in this chapter: it aims at minimizing network and routing costs over a multiperiod location and routing decision vector. However, multi-echelon location routing problems (e.g. [115, 116]) have only recently gathered attention in the literature. Although multi-echelon networks are relevant to postal and parcel delivery distribution systems ([117]) where fine time constraints and synchronization have become an essential consideration, most papers studying multi-echelon networks are concerned with the two-echelon case and ignore temporal aspects ([113]).

When allowing inter-location capacity pooling, underlying operations described in section 4.1 are impacted. Couriers perform pickup and delivery tours starting and ending in their reference access hub, while riders visit access hubs starting and ending their routes in their reference local hub. The impact of capacity pooling can be measured by modeling its impact on the route of parcels, couriers and riders. However, when taking decisions at the tactical level, explicitly modeling routes is not necessary. TSP and VRP continuous approximations have been introduced by [118, 119] to embed operations in strategic and tactical logistics problems (e.g. [120], [121]). A recent literature on variants of this approach can be found in [93]. [91, 92, 122] adapted these continuous approximations to the context of parcel express logistics to approximate distance traveled and cost. However, the aspect of synchronization using travel time continuous approximations has not yet been studied. To the best of the authors' knowledge, this chapter is the first to study a capacity relocation problem with the synchronization of two-echelon routing operations through travel time estimates.

4.3 Problem Description and Formulation

4.3.1 Business Context

A parcel logistics company provides pickup and delivery services to customers in a region covered by a network of access hubs. The network of access hubs may be dedicated to the parcel logistics provider, or shared between several companies as suggested by the concept of open networks in the Physical Internet. Figure 4.2 provides a conceptual illustration of the network of access hubs and the relocation of modular capacity modules over two consecutive deployment periods subject to variations of demand. Once the network capacity is set, pickups from customers are dropped off by couriers in access hubs and will occupy a certain storage volume for some time until a rider picks them up to perform outbound activities. To-be-delivered parcels are dropped off by riders in access hubs and will occupy a certain storage volume for some time until a courier picks them up to perform the delivery to customers. To provide good service, the company must ensure that parcels flow rapidly and seamlessly between couriers and riders, which requires the sound management of storage capacity deployed in access hubs. Storage volume requirements vary depending on the fluctuation of demand for pickup and delivery services over time and are observed over a discrete set of operational periods (e.g. hourly). Access hubs are composed of modular storage units that can be assembled and disassembled relatively easily, enabling rapid relocation of storage capacity in the network. During each deployment period (e.g. week or day), storage capacity can be relocated within the network of access hubs, or to/from a depot where additional capacity modules are stored when not in use. Figure 4.2 illustrates demand variability and the relocation of capacity modules within the network of access hubs over two deployment periods. For instance, unit zones with increasing demand (and therefore increasing capacity requirements) from period t to $t+1$ receive capacity module(s) from the depot of from locations that have decreasing capacity requirements (e.g. lower left unit zone in Figure 4.2).

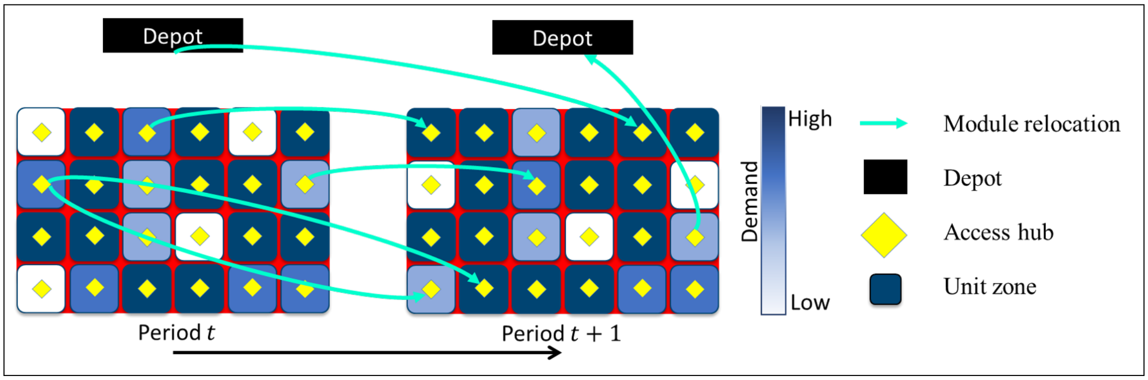


Figure 4.2: Illustration of Access Hub Modular Capacity Relocation Between Two Consecutive Tactical Periods

The relocation of capacity modules over the network adjusts the storage capacity available in each access hub for the following period. Relocations are to be performed between two consecutive tactical periods (i.e. overnight). In this study, we assume capacity module relocation is performed by a separate business unit whose routing decisions are out of the scope of the research reported in this chapter.

The objective is to minimize the cost incurred by operating such a network of access hubs without disrupting underlying operations. The decision scope is tactical (capacity deployment) and requires the integration of operational decisions. However, since the main interest is a set of tactical decisions, there is no need to explicitly model operations, but only to approximate the impact of deployment decisions on routing cost and time synchronization.

Let L be a set of access hub locations and W a set of external depots composing a network $G = (N = L \cup W, A)$ where A is the complete set of directed arcs between locations in N. A capacity deployment of I_0 capacity modules in time t over the network is represented by a vector $S(t) = (S_l(t), \forall l \in N)$. The relocation of capacity modules can be represented as vectors $R(t) = (R_a(t), \forall a \in A)$. Accordingly, there are $\binom{I_0+|L|-1}{I_0}$ possible arrangements of I_0 modules over $|L|$ locations. In the case where $I_0 \geq |L|$ and that each location gets at least one module, there are $\binom{I_0-1}{|L|-1}$ possible arrangements. In this realistic context, access hub networks are expected to be composed of a high number of locations (i.e., hundreds). Thus, state and action spaces would be significantly large-sized, which results in curse of dimensionality issues ([123]).

Moreover, a set of demand realization scenarios $\omega \in \Omega$ with probability ϕ_ω is considered. The number of pickups and deliveries as well as the storage volume requirements are observed hourly and respectively represented as a vectors $\rho^P(\tau,\omega) = (\rho_l^P(\tau,\omega), \forall l \in L)$, $\rho^D(\tau,\omega) = (\rho_l^D(\tau,\omega), \forall l \in L)$ and $D(\tau,\omega) = (D_l(\tau,\omega), \forall l \in L)$, for every operations hour $\tau \in T_t$, where $t \in T$ is an operations horizon between two deployment periods (e.g. a week). If a courier or rider observes a lack of storage capacity when visiting an access hub, the courier or rider can perform the following recourse actions: pool capacity by making a detour towards a neighboring access hub with extra capacity or consign its load to a nearby third-party business (e.g. local shop) for a certain price agreed upon (uncapacitated recourse). Once volume requirements are observed, recourse actions are taken for each operational period τ: capacity pools as a vector $P(\tau,\omega) = (P_a(\tau,\omega), \forall a \in A_{pool})$ where A_{pool} is the set of arcs on which capacity can be pooled, and consignments as a vector $Z(\tau,\omega) = (Z_l(\tau,\omega), \forall l \in L)$. At any time τ in scenario ω, the system can thus be represented as a state $S_t = S(t)$ s.t. $\tau \in T_t$ and an action $x_\tau = (R(\tau), P(\tau,\omega), Z(\tau,\omega))$ s.t. $\tau \in T_t$, where $R(\tau)$ is the null vector except for $\tau = t, \forall t \in T$. Based on the optimisation framework proposed in [124], our stochastic optimization challenge for the access hub dynamic pooled capacity deployment problem can be formulated as follows:

$$\min_{x_\tau \in X(\tau)} \mathop{\mathbb{E}}_{\omega \in \Omega} \left\{ \sum_{t \in T} \sum_{\tau \in T_t} C_\tau(S_t, x_\tau, \rho^P(\tau,\omega), \rho^D(\tau,\omega), D(\tau,\omega)) | S_0 \right\} \tag{4.1}$$

where $X(\tau)$ is the set of feasible actions at time τ, S_0 is the initial state of the system, and

$C_\tau(\cdot)$ is the cost function at time τ. Figure 4.3 illustrates the dynamics of the problem with the tactical decision timeline: before each period t, a network deployment strategy $S(t)$ is decided through relocation decisions $R(t)$ and implemented right before the beginning of period t. Then, demand realized and recourse actions are taken in each period $\tau \in T_t$. At the end of periods T_t, a network deployment strategy $S(t+1)$ is decided through relocation decisions $R(t+1)$ and implemented right before the beginning of period $t+1$ and the process repeats.

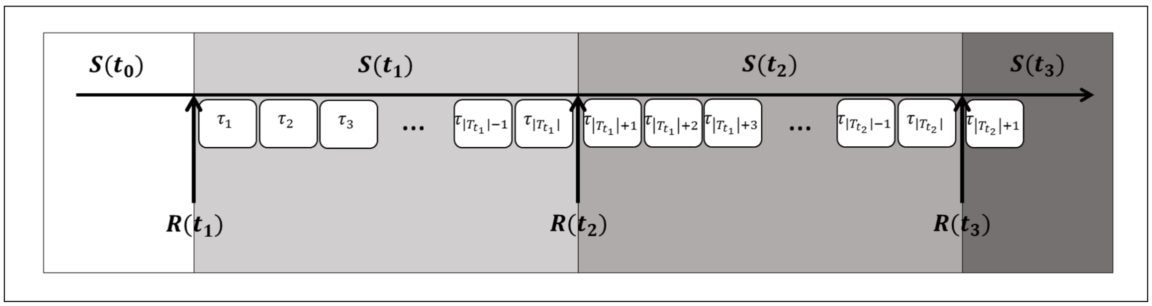


Figure 4.3: Timeline of the Hyperconnected Access Hub Network Dynamic Storage Capacity Deployment Problem

4.3.2 Operations Cost Approximation and Synchronization Modeling

Once decisions on capacity deployment are set for a given period t, they strongly impact the quality of operations performed by couriers and riders. More specifically, capacity at each location impacts the number and costs of detour and perturb the synchronisation of the operations between couriers and riders at each location. Accordingly, the surrounding objective of integrating routing operations is to evaluate the performance of the capacity deployment in minimizing the detours due to an underestimation of the capacity needs and in guaranteeing the synchronisation of the operations between couriers and riders at each location. To do so, this subsection proposes to develop routes with detours cost approximations, and travel time approximations. It builds on a refined granularity of routing operations periods (hourly) and uncertain storage volume requirements.

Figure 4.4 illustrates the use of access hubs in first/last mile parcel logistics operations during a period τ with one rider and 3 couriers. At the operational level, pickup and delivery decisions are made hourly (τ) based on the volume-based capacity made available at each access hub. In addition, capacity relocation determines the number and costs of recourse actions needed to satisfy the requested volumes. With the consideration of capacity pooling recourse, the pickup and delivery problem with transshipment faced by couriers and riders adds the feature of detours. Here, to ensure timely transshipment operations, the detours performed by couriers and riders, are limited to their original time period (τ), avoiding couriers and riders to be desynchronized. Since these detours necessitate additional moves and are time consuming, this comes with a supplementary incurred cost.

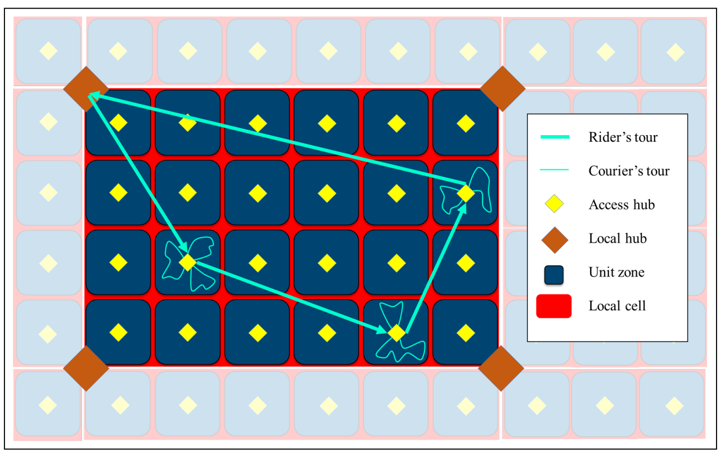


Figure 4.4: Illustration of Couriers and Riders Operations

It is clear that capturing the dynamics of underlying operations when taking capacity deployment decisions leads to better solutions. However, the pickup and delivery problem with transshipment is NP-hard [125] and including it explicitly in the tactical model would make it intractable. Since the goal is to foster best capacity deployment decisions, it is sufficient to anticipate the operations costs and time synchronisation constraints using scenario-based continuous approximations.

Accordingly, hereafter is proposed a tractable approximation of each period τ pickup and delivery problem with transshipment by developing deterministic continuous approximations of vehicle routing problems. The starting point of the proposed approximations is the estimation of the vehicle routing problem length when the depot (from which vehicles start their routes) is not necessarily located in the area where customers are located as proposed in [118]:

$$VRP(n) = 2rm + nk(\delta)^{-\frac{1}{2}} \tag{4.2}$$

where r is the average distance between the depot and the customer locations, m is the number of routes required to serve all customers, n is the number of points to be visited, k is a constant parameter that can be estimated through simulation ([119]), and δ is the density of points in the area. An a priori lower bound on the number of routes required to serve all customers, m, is n/Q where Q is the capacity of one vehicle in terms of customer locations. The first term of approximation (4.2) represents the line-haul (back and forth) performed by vehicle to travel from the depot to the area where customers are located, and the second term represents the tour performed by traveling between each successive stops. Based on these seminal works, the next subsection proposes an adaptation of these equations to the operational context of riders and couriers, and develops an explicit time-based estimation of their operations.

Riders operations

Riders work in local cells, which are clusters of access hubs served by the same upper level local hub(s) as illustrated in Figure 4.5. Riders visit a set of n_{LC} access hubs within their local cell of area A_{LC} (and density $\delta_{LC} = \frac{n_{LC}}{A_{LC}}$) to pickup and deliver parcels as part of a defined route (e.g. planned beforehand based on averaging network's load). At the time of deployment, underlying riders' routes are not known with certainty, but need to be estimated in order to anticipate operations performance. When a rider makes his tour in period τ under scenario ω two cases are possible: (i) the tour is operated as planned because sufficient capacity is deployed at all visited access hubs in the route or because the detours are assigned to access hubs that are already in the remaining itinerary of the rider (bold lines in Figure 4.5); (ii) the rider tour is perturbed due to a lack of capacity at an access hub, and thus has to perform an immediate detour to a neighboring access hub before pursuing the rest of the regular tour (dash lines in Figure 4.5).

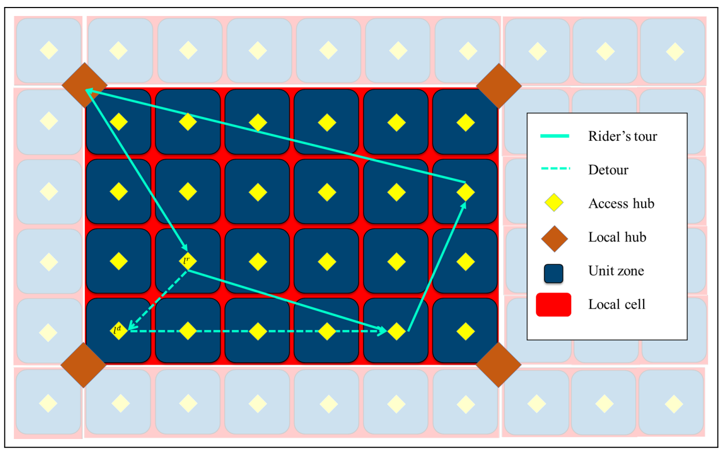


Figure 4.5: Illustration of a Rider's Tour with Detour

Given approximation (4.2), if the number of detours performed by riders in local cell LC in period τ in scenario ω is $n^R_{LC}(\tau,\omega)$, the route length estimation with detours of riders' operations is:

$$VRP^R_{LC}(\tau,\omega) = 2r_{LC}m^R_\tau(\omega) + (n_{LC} + n^R_{LC}(\tau,\omega))k^R(\delta_{LC})^{-\frac{1}{2}} \tag{4.3}$$

where n_{LC} is the total number of access hubs in local cell LC, r_{LC} is the average distance between LC's local hub(s) and its access hubs, and $m^R_\tau(\omega)$ is the number of riders' operating.

The cumulative time (in time-rider) necessary to perform tours approximated in (4.3) is:

$$T^R_{LC}(\tau,\omega) = m^R_\tau(\omega)(t^R_s + \frac{2r_{LC}}{s^R_0}) + (n_{LC} + n^R_{LC}(\tau,\omega))(\frac{k^R(\delta_{LC})^{-\frac{1}{2}}}{s^R} + t^R_a)$$
$$+(\sum_{l\in LC}(\rho^D_l(\tau,\omega) + \rho^P_l(\tau,\omega)))t^R_u \qquad (4.4)$$

where the first term is the time spent to setup tours (t^R_s per tour) and perform the line-haul at a speed of s^R_0, the second term represent the travel time between stops at a speed of s^R and the stopping time t^R_a per access hub, and the third term represents the service time (handling) t^R_u per pickup and delivery.

Thus, the cost associated with riders' operations in local cell LC in period τ in scenario ω is:

$$C^R_{LC}(\tau,\omega) = m^R_\tau(\omega)(c^R_f + 2r_{LC}c^R_{v_0}) + (n_{LC} + n^R_{LC}(\tau,\omega))k^R(\delta_{LC})^{-\frac{1}{2}}c^R_v + T^R_{LC}(\tau,\omega)c^R_w \quad (4.5)$$

where the first term represents the fixed, c^R_f, and variable, $c^R_{v_0}$ in line-haul and c^R_v in tour, costs associated with vehicles, and the second term represents the variable labor cost c^R_w of $m^R_\tau(\omega)$ riders.

Since the nominal routing cost (with no detours) is a sunk cost incurred regardless of the capacity deployment, the marginal cost is sufficient to inform the tactical decision of the impact of recourse actions. The marginal cost of the detours induced by the tactical decisions, or difference between the rider routing cost with detours and the nominal rider routing cost, is:

$$\Delta C^R_{LC}(\tau,\omega) = n^R_{LC}(\tau,\omega)k^R(\delta_{LC})^{-\frac{1}{2}}c^R_v + \Delta T^R_{LC}(\tau,\omega)c^R_w \qquad (4.6)$$

where the time associated with performing detours is the time needed to perform detours:

$$\Delta T_{LC}^{R}(\tau,\omega) = n_{LC}^{R}(\tau,\omega)(\frac{k^{R}(\delta_{LC})^{-\frac{1}{2}}}{s^{R}} + t_{a}^{R}) \tag{4.7}$$

Couriers operations

Couriers operate in unit zones, which are clusters of pickup and delivery points served by access hub(s). Couriers leave their reference access hubs to visit customers and perform pickups/deliveries before returning to their access hub. When a courier arrives at the couriers access hub with picked parcels, if the courier observes a lack of capacity, the courier can be immediately directed to available capacity in some neighboring access hub. Then, the courier will perform a detour (out and back) to the assigned neighbour access hub before starting their next tour from their reference access hub. Figure 4.6 illustrates a courier's tour and a detour as described.

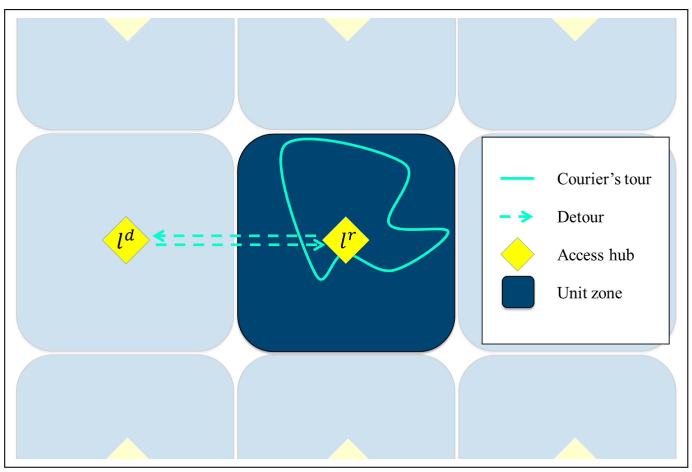


Figure 4.6: Illustration of a Courier's Tour with Detour

Since access hubs are located in the same area as pickup/delivery locations, the line-haul distance at this echelon is negligible, which eliminates the first term of approximation (4.2). If the number of detours performed by couriers on arc $a \in A_{pool}(l) = \{a = (l,j), \forall j : (l,j) \in A_{pool}\}$ of length d_a in period τ under scenario ω is $n_a^C(\tau,\omega)$, the route length estimation with detours of couriers' operations is:

$$VRP_l^C(\tau,\omega) = (\rho_l^P(\tau,\omega) + \rho_l^D(\tau,\omega))k^C(\delta_l)^{-\frac{1}{2}} + \sum_{a\in A_{pool}(l)} (2n_a^C(\tau,\omega)d_a) \tag{4.8}$$

where the first term represents the total length of tours performed by couriers to visit pickup/delivery locations, and the second term represents the detours (out and back) performed between access hub l and its neighboring access hubs.

The cumulative time (in time-courier) necessary to perform courier tours is based on the approximation in (4.8) as follows:

$$\begin{aligned} T_l^C(\tau,\omega) = (\rho_l^P(\tau,\omega) + \rho_l^D(\tau,\omega))(\frac{k^C(\delta_l)^{-\frac{1}{2}}}{s^C} + t_a^C) + \sum_{a\in A_{pool}((l)} n_a^C(\tau,\omega)(\frac{2d_a}{s_0^C} + t_a^C) \\ +(\rho_l^D(\tau,\omega) + \rho_l^P(\tau,\omega))t_u^C \end{aligned} \tag{4.9}$$

where the first term represents the travel time between pickup/delivery locations at a speed of s^C and the stopping time t_a^C per stop, the second term represents the travel time during detours to neighboring access hubs at a speed of s_0^C plus a stopping time t_a^C, and the third term represents the service time (handling) t_u^C per pickup and delivery.

Thus, the cost associated with couriers' operations at access hub l in period τ under scenario ω is:

$$C_l^C(\tau,\omega) = ((\rho_l^P(\tau,\omega) + \rho_l^D(\tau,\omega))k^C(\delta_l)^{-\frac{1}{2}}c_v^C + \sum_{a\in A_{pool}(l)} (2n_a^C(\tau,\omega)d_a)c_{v_0}^C) + T_l^C(\tau,\omega)c_w^C \tag{4.10}$$

where the first term represents the variable travel costs, respectively c_v^C between pickup and delivery locations and $c_{v_0}^C$ between access hubs, and the second term represents the variable labor cost c_w^C of $m_\tau^C(\omega)$ couriers.

Again, since the nominal routing cost (with no detours) is a sunk cost incurred regardless of the capacity deployment, the marginal cost is sufficient to inform the tactical decision of the impact of recourse actions.The marginal cost of the detours induced by the tactical decisions, or the difference between the courier routing cost with detours and the nominal courier routing cost is:

$$\Delta C_l^C(\tau,\omega) = \sum_{a \in A_{pool}(l)} (2n_a^C(\tau,\omega)d_a)c_{v_0}^C) + \Delta T_l^C(\tau,\omega)c_w^C \tag{4.11}$$

where the time associated with performing detours is:

$$\Delta T_l^C(\tau,\omega) = \sum_{a \in A_{pool}(l)} n_a^C(\tau,\omega)(\frac{2d_a}{s_0^C} + t_a^C) \tag{4.12}$$

Operations Synchronization

Recall that a key objective of integrating routing operations with the capacity deployment problem is to guarantee the synchronisation of the operations between couriers and riders at each location. To do so, this subsection proposes to develop time-based synchronisation constraints based on the travel time approximations (4.4) and (4.9), developed above.

Parcels transshipped from riders to couriers and couriers to riders through access hubs must be transshipped during the period of time the parcels are within the network. That is, the length of a courier's (respectively rider's) original tour, plus the added detour(s) must not exceed the maximum length feasible within one operational period. For riders operations, at the local cell level, this tour length can be expressed, based on the number of riders ($m_\tau^R(\omega)$ in period τ under scenario ω, as follows:

$$T_{LC}^R(\tau,\omega) \leq m_\tau^R(\omega)\Delta_\tau, \forall \omega \in \Omega, LC \in \mathcal{LC}, \tau \in T_t, t \in T \tag{4.13}$$

where Δ_τ is the length of period τ. Similarly, for couriers' operation, at the access hub level, synchronization can be expressed, based on the number of couriers ($m_\tau^C(\omega)$ in period τ under scenario ω, as follows:

$$T_l^C(\tau,\omega) \leq m_\tau^C(\omega)\Delta_\tau, \forall \omega \in \Omega, l \in L, \tau \in T_t, t \in T \tag{4.14}$$

4.3.3 Two-Stage Stochastic Program Formulation for the Access Hub Dynamic Pooled Capacity Deployment Problem

In this section, a stochastic programming formulation is proposed to tackle the optimization problem (4.1) presented in section 4.3.1. We remark that the stochastic optimisation problem (4.1) can be modeled as a multi-stage stochastic program based on a scenarios tree. However, this program would be intractable for realistic size instances, due to its combinatorial structure and non-anticipatory constraints [126]. Under a rolling horizon framework, the model is built here on the relaxation approach [127] that is applied to transform the multi-stage stochastic program to a two-stage stochastic program with multiple tactical periods. More specifically, it consists in transferring all the capacity deployment decisions of the T periods to the first-stage in order to be set at the beginning of the horizon. In this case, only first-stage design decisions ($t = 1$) are made here and now, but subsequent capacity deployment decisions ($t > 1$) are deferrable in time according to their deployment period. Hereafter are introduced the additional sets, input parameters, random variables and decision variables that formulate the overall model.

Sets

$\mathcal{L}$	access hub locations, indexed by l
$\mathcal{LC}$	local cells, indexed by LC
$\mathcal{W}$	depot locations, indexed by l
$\mathcal{A}$	arcs between two locations of the network $\mathcal{L} \cup \mathcal{W}$, indexed by a

$\mathcal{G}$	asymmetric graph $(\mathcal{L} \cup \mathcal{W}, A)$ satisfying the triangle inequality
T	tactical periods, indexed by t, covering the planning horizon
T_t	subset of operational periods, indexed by τ, between periods t and $t+1$
Ω	scenarios, indexed by ω
$\delta^+(l)$	incoming relocation arcs in location $l \in \mathcal{G}$
$\delta^-(l)$	outgoing relocation arcs from location $l \in \mathcal{G}$
$N^+(l)$	incoming recourse arcs in location l ; $N^+(l) \subset \delta^+(l)$
$N^-(l)$	outgoing recourse arcs from location l ; $N^-(l) \subset \delta^-(l)$
$A_{pool}(l)$	recourse arcs available for capacity pooling from location l

Input Parameters

h_l	cost of holding one capacity module at location l.
I_0	total number of capacity modules available in the system
ϕ_ω	probability of scenario ω
p_l	penalty for lacking capacity in location l
r_a	cost of relocating one capacity module on a.
$\overline{S_l}$	maximum number of capacity modules that can be placed in location l
v	volume provided by a capacity module
v^R	volume that a rider can carry on a tour
v^C	volume that a courier can carry on a tour

Random Variables

$D_l(\tau, \omega)$	volume requirements in location l in scenario ω in period (τ)

Decision Variables

$S_l(t)$	number of capacity modules available in location l for period t
$R_a(t)$	number of capacity modules relocated through arc a at the beginning of period t
$P_a(\tau, \omega)$	volume shared from location i to j, $a = (i, j) \in N^-_{\omega,\tau}(i)$ in period τ under scenario ω
$Z_l(\tau, \omega)$	lack of capacity in volume at location l in period τ under scenario ω
$n^R_a(\tau, \omega)$	number of detours performed by riders on arc a in period τ under scenario ω
$n^R_{LC}(\tau, \omega)$	number of detours performed by riders in local cell LC in period τ under scenario ω
$n^C_a(\tau, \omega)$	number of detours performed by couriers on arc a in period τ under scenario ω
$n^C_l(\tau, \omega)$	number of detours performed by couriers from location l in period τ under scenario ω

Model

$$\min \sum_{t \in T} \Bigg(\sum_{l \in \mathcal{L} \cup \mathcal{W}} h_l S_l(t) + \sum_{a \in A} r_a R_a(t) + \sum_{\omega \in \Omega} \phi_\omega \Bigg(\sum_{\tau \in T_t} \Bigg(\sum_{l \in L} (\Delta C^C_l(\tau, \omega) + p_l Z_l(\tau, \omega)) + \sum_{LC \in \mathcal{LC}} \Delta C^R_{LC}(\tau, \omega) \Bigg) \Bigg) \Bigg) \tag{4.15}$$

s.t.:

Inventory balance of capacity modules at all locations:

$$S_l(t) = S_l(t-1) + \sum_{a \in \delta^+(l)} R_a(t) - \sum_{a \in \delta^-(l)} R_a(t), \forall l \in \mathcal{L} \cup \mathcal{W}, t \in T \tag{4.16}$$

Total capacity module inventory constraint:

$$\sum_{l \in \mathcal{L} \cup \mathcal{W}} S_l(t) = I_0, \forall t \in T \tag{4.17}$$

Spatial constraint at all locations:

$$S_l(t) \leq \overline{S_l}, \forall l \in \mathcal{L}, t \in T \tag{4.18}$$

Volume requirements satisfaction constraints:

$$vS_l(t) + \sum_{a \in N^+(l)} P_a(\tau, \omega) - \sum_{a \in N^-(l)} P_a(\tau, \omega) + Z_l(\tau, \omega) \geq D_l(\tau, \omega),$$
$$\forall l \in L, \tau \in T_t, t \in T, \omega \in \Omega \tag{4.19}$$

Synchronization constraint for riders' operations: (4.13)

Synchronization constraint for couriers' operations: (4.14)

Rider's detours count:

$$n^R_{LC}(\tau, \omega) \geq \sum_{l \in LC} \sum_{a \in A_{pool(l)}} n^R_a(\tau, \omega), \forall LC \in \mathcal{LC}, \tau \in T_t, t \in T, \omega \in \Omega \tag{4.20}$$

$$n^R_a(\tau, \omega) \geq \frac{P_a(\tau, \omega)}{v^R}, \forall a \in A_{pool}(l), l \in L, \tau \in T_t, t \in T, \omega \in \Omega \tag{4.21}$$

Courier's detours count:

$$n^C_l(\tau, \omega) \geq \sum_{a \in A_{pool}(l)} n^C_a(\tau, \omega), \forall l \in L, \tau \in T_t, t \in T, \omega \in \Omega \tag{4.22}$$

$$n^C_a(\tau, \omega) \geq \frac{P_a(\tau, \omega)}{v^C}, \forall a \in A_{pool}(l), l \in L, \tau \in T_t, t \in T, \omega \in \Omega \tag{4.23}$$

Integrality and non-negativity constraints:

$$P_a(\tau, \omega), Z_l(\tau, \omega), n^C_a(\tau, \omega), n^R_a(\tau, \omega), n^C_l(\tau, \omega) \geq 0 \tag{4.24}$$

$$S_l(t), R_a(t) \text{ integer} \tag{4.25}$$

Minimizing expression (4.15) corresponds to minimizing the last-mile cost, defined in this chapter as the cost of deploying capacity modules in each access hub locations (holding costs) and the relocation costs for each capacity module movement for each reconfiguration period, and the marginal cost incurred by recourse actions (capacity pool from neighboring location and consignment). Constraints (4.16) and (4.17) enforce the conservation of the total number of capacity modules in the network. Constraints (4.18) limit the number of capacity modules that can be deployed in each access hub locations. Constraints (4.19) enforce that all demand in terms of volume requirement is served by a combination of capacity modules, capacity pools and consignments, in each demand period of each scenario. Constraints (4.13) and (4.14) are the synchronization constraints for the underlying riders and couriers problems as developed in section (4.3.2). Constraints (4.21) and (4.22) count the number of detours performed by riders within each local cell based on recourse capacity pooling decisions and the carrying capacity of riders. Constraints (4.23) and (4.24) count the number of detours performed by couriers from each access hub based on recourse capacity pooling decisions and the carrying capacity of couriers.

4.4 Solution Approach

In this section, our rolling horizon solution approach is presented, which builds on solving sequentially the two-stage model presented above using scenario sampling, Benders decomposition and acceleration methods. It approximates optimization problem (4.1) by planning for one capacity deployment period, t, at the time and deferring subsequent capacity deployment decisions to the following iterations of the Algorithm. In order to enhance the quality of the solutions produced at each iteration, a θ tactical lookahead is considered to plan for $1 + \theta$ tactical periods, where only the first period is implementable and the subsequent ones are used as an evaluation mechanism. The proposed rolling horizon solution approach is described in Algorithm 1. Here, the length of the sub-horizon is controllable; it can represent one tactical period (i.e. myopic, $\theta = 0$) or several of them (i.e. lookahead, $\theta \geq 1$). Of course, when dealing with large-scale networks, the selection of the lookahead length is part of the trade-offs necessary to make in order to keep the model tractable. In order to enhance the solvability of the optimization model (4.15-4.25), for each sub-horizon $[t, t+\theta]$, a tailored Benders decomposition approach is developed, that fits with the two-stage and multi-period setting of our formulation. It is applied under a large sample of multi-period scenarios. The following subsections address the decomposition approach as well as the associated acceleration methods developed.

Algorithm 1: Rolling Horizon Algorithm with Tactical Lookahead

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Result: $S_l(t), R_a(t)$
$S_l(t_0) \longleftarrow S_l(t_0)$;
for $t \in T$ **do**
  $S_l(t), R_a(t) \longleftarrow$ Optimal solution of (4.15-4.25) for sub-horizon $[t, t+\theta]$;
end

4.4.1 Benders Decomposition

Benders decomposition is a row generation solution method for solving large scale optimization problems by partitioning the decision variables in first stage and second stage variables ([128]). The model is first projected onto the subspace defined by the first stage variables, replacing the second stage variables by an incumbent; the resulting model is called the restriced master problem. Then, a linear problem with the second stage variables and a candidate solution from the restricted master problem is formulated; the resulting model is called the subproblem and can often be decomposed in independent subproblems. From the solution of the subproblem, feasibility and optimality cuts can be identified and added to the restricted master problem. The algorithm terminates when the incumbent in the restriced master problem is equal to the the value of the subproblem. Suppose the capacity deployment and relocation decisions (first stage decision variables) $S_l(t)$, $S_l(t+1)$, ... ,$S_l(t+\theta)$ and $R_a(t)$, $R_a(t+1)$, ..., $R_a(t+\theta)$ are given with values $\widehat{S_l}(t)$,

$\widehat{S_l}(t+1)$, ... , $\widehat{S_l}(t+\theta)$ and $\widehat{R_a}(t)$, $\widehat{R_a}(t+1)$, ..., $\widehat{R_a}(t+\theta)$. Then, the subproblem can be defined as taking recourse action decisions (i.e. second stage decisions; capacity pooling) to minimize the approximate overall operations costs. The subproblem can be decomposed per scenario ω, operational period τ and local cell LC into a set of independent subproblems as follows:

$$SP_{LC}(\tau,\omega) = \min \sum_{l \in L(LC)} (\Delta C_l^C(\tau,\omega) + p_l Z_l(\tau,\omega)) + \Delta C_{LC}^R(\tau,\omega) \quad (4.26)$$

s.t.:

Volume requirements satisfaction constraints:

$$v\widehat{S_l}(t) + \sum_{a \in N^+(l)} P_a(\tau,\omega) - \sum_{a \in N^-(l)} P_a(\tau,\omega) + Z_l(\tau,\omega) \geq D_l(\tau,\omega), \quad \forall l \in L(LC) \quad (4.27)$$

Synchronization constraint for riders' operations: (4.13)

Synchronization constraint for couriers' operations: (4.14)

Detour linking constraints: (4.21), (4.22), (4.23), (4.24)

$$P_a(\tau,\omega), Z_l(\tau,\omega), n_a^C(\tau,\omega), n_a^R(\tau,\omega), n_l^C(\tau,\omega) \geq 0$$

It is important to notice that the defined subproblems are feasible regardless of the value of the tactical decisions (first stage variables); This is possible thanks to the variables $Z_l(\tau,\omega)$ that compensate for any lack of capacity in the network by incurring a large cost.

Solving each subproblem using a dualization strategy, one can identify the following optimality cuts for each local cell, operational period τ and scenario ω:

$$q_{LC}(\tau,\omega) \geq \sum_{l \in L(LC)} \pi_l^j(\tau,\omega)(D_l(\tau,\omega) - vS_l(t)) \quad (4.28)$$

$$+ \mu_{LC}^{j}(\tau,\omega)\Big(m^R(\tau,\omega)(\Delta_\tau - (t_s^R + \frac{2r_{LC}}{s_0^R})) - n_{LC}(\frac{k^R(\delta_{LC})^{-\frac{1}{2}}}{s^R} + t_a^R)$$

$$- \sum_{l\in LC}(\rho_l^D(\tau,\omega) + \rho_l^P(\tau,\omega))t_u^R\Big)$$

$$+ \sum_{l\in L(LC)}\Big(\lambda_l^j(\tau,\omega)(m^C(\tau,\omega)\Delta_\tau$$

$$- (\rho_l^P(\tau,\omega) + \rho_l^P(\tau,\omega))(\frac{k^C(\delta_l)^{-\frac{1}{2}}}{s^C} + t_a^C + t_u^C))\Big)$$

where $j \in J$, the set of extreme points of the dualized subproblem; $\pi_l^j(\tau,\omega)$, $\mu_{LC}^j(\tau,\omega)$ and $\lambda_l^j(\tau,\omega)$ are the dual values respectively associated with constraints (4.27), (4.13) and (4.14).

Finally, the restricted master problem, whose objective minimizes the cost of deploying capacity modules in each access hub and the relocation costs for each capacity module for each period subject to the optimality cuts, can be formulated as follows:

$$RMP = \min \sum_{t}^{t+\theta}\Big(\sum_{l\in\mathcal{L}\cup\mathcal{W}} h_l S_l(t) + \sum_{a\in A} r_a R_a(t) + \sum_{\omega\in=\Omega}\phi_\omega \sum_{\tau\in T_t}\sum_{LC\in\mathcal{LC}} q_{LC}(\tau,\omega)\Big) \quad (4.29)$$

s.t.:

Inventory balance of capacity modules at all locations: (4.16)

Total capacity module inventory constraint: (4.17)

Spatial constraint at all locations: (4.18)

Optimality cuts: (4.28), $\forall j \in \overline{J} \subset J$ (4.30)

$S_l(t), R_a(t)$ integer

Solving the restriced master problem with added optimality cuts provides new values $\widehat{S_l}(t)$ and $\widehat{R_a}(t)$, and a new incumbent solution. This process can be executed iteratively until the incumbent solution equals the subproblem value, indicating optimality.

4.4.2 Acceleration Methods

The following subsection describes acceleration methods developed to improve the performance of the proposed solution approach on large instances. The acceleration techniques retained are those that improve significantly the convergence speed of the benders decomposition algorithm for the proposed model.

Pareto-optimal Cuts

The proposed implementation of the benders decomposition can be improved using Pareto-optimal cuts, which requires to solve two linear programs: the original subproblem (4.26), and the Pareto subproblem. The result is the identification of the strongest cut when the original subproblem solution has multiple solutions. A Pareto-optimal solution produces the maximum value at a core point, which is required to be in the relative interior of the convex hull of the subregion defined by the first stage variables. The Pareto subproblem can be decomposed per scenario ω, operational period τ and local cell LC in a set of independent Pareto subproblems as follows:

$$\min \sum_{l \in L(LC)} (\Delta C_l^C(\tau,\omega) + p_l Z_l(\tau,\omega)) + \Delta C_{LC}^R(\tau,\omega) + v_{SP} Y \tag{4.31}$$

s.t.:

$$v(S_l^0(t) + \sum_{a \in N^+(l)} P_a(\tau,\omega) - \sum_{a \in N^-(l)} P_a(\tau,\omega) + Z_l(\tau,\omega) + (D_l(\tau,\omega) - v\widehat{S}_l(t))Y \geq D_l(\tau,\omega), \forall l \in L(LC) \tag{4.32}$$

Modified synchronization constraint for riders' operations:

$$T_{LC}^R(\tau,\omega) \leq m^R(\tau,\omega)\Delta_\tau(1-Y) + \left(m_\tau^R(\omega)\left(t_s^R + \frac{2r_{LC}}{s_0^R}\right) + n_{LC}\left(\frac{k^R(\delta_{LC})^{-\frac{1}{2}}}{s^R} + t_a^R\right) + \left(\sum_{l \in LC} (\rho_{l\tau}^D(\omega) + \rho_{l\tau}^P(\omega))\right) t_u^R\right) Y \tag{4.33}$$

Modified synchronization constraint for couriers' operations:

$$T_l^C(\tau,\omega) \le m^C(\tau,\omega)\Delta_\tau(1-Y) + \left((\rho_{l\tau}^P(\omega) + \rho_{l\tau}^P(\omega)) \left(\frac{k^C(\delta_l)^{-\frac{1}{2}}}{s^C} + t_a^C + t_u^C \right) \right) Y,$$
$$\forall l \in L(LC) \qquad (4.34)$$

Detour linking constraints: (4.21), (4.22), (4.23), (4.24)

$P_a(\tau,\omega), Z_l(\tau,\omega), n_a^C(\tau,\omega), n_a^R(\tau,\omega), n_l^C(\tau,\omega), Y \ge 0$

where v_{SP} is the value of the corresponding original subproblem and $S_l^0(t)$ a core point of the current solution to the restricted master problem. Solving each Pareto subproblem using a dualization strategy, one can identify strengthened optimality cuts (4.28) by assigning $\pi_l^j(\tau,\omega)$, $\mu_{LC}^j(\tau,\omega)$ and $\lambda_l^j(\tau,\omega)$ the dual values respectively associated with constraints (4.32), (4.33) and (4.34).

The proposed implementation also updates the core point, which can be seen as an intensification procedure: locations that are rarely given capacity modules decay toward low values while locations with consistent capacity module presence in every solution are assigned a high coefficient in Pareto solutions. The update rule was introduced in [129], and consists of updating the core point at iteration k, $S^{0(k)}$ by combining it with the solution of the master problem at this iteration, $\widehat{S}^{(k)}$, using a factor λ. [130] suggest that a factor $\lambda = 1/2$ yields the best results. The update rule is defined as follows:

$$S_l^{0(k+1)}(t) = \frac{S_l^{0(k)}(t) + \widehat{S}_l^{(k)}(t)}{2}, \forall l \in L, t \in T$$
$$S_l^{0(k+1)}(t) = \frac{I_0 - \sum_{l' \in L} S_{l'}^{0(k+1)}(t)}{|W|}, \forall l \in W$$

where k is the current iteration of the Benders algorithm.

ϵ-optimal Method

When dealing with large-scale instances, the ϵ-optimal method as described in [131] has proven to speed up the proposed Benders decomposition algorithms by avoiding to solve the restricted master problem to optimality at each iteration, while guaranteeing an optimal gap within ϵ. It is not necessary to solve the restricted master problem to optimality at each iteration to generate good quality cuts, and there is no incentive to do so at the beginning of the algorithm because the relaxation is weak. Instead, the restricted master problem can be solved with a relaxed optimality gap by adding a constraint forcing the objective value to be improved by at least $\widehat{\epsilon}$ percent compared to the previous solution. Then, when no feasible solution is found, $\widehat{\epsilon}$ is decreased. The same mechanism is applied until ϵ is reached; the algorithm terminates when no feasible solution is found to the restricted master problem, guaranteeing that the current solution is within ϵ of the optimal.

4.5 Experimental Results

In this section, the results of numerical experiments are presented in order to validate the developed modeling and solution approaches, and to analyze the performance of the proposed capacity deployment strategy for urban parcel logistics. After describing the test instances which are inspired from the real data of a large parcel express carrier, experimental results about the computational performance of the solution approach are presented. Then, the performance of the dynamic pooled capacity deployment strategy is exposed and compared to its static counterpart. Finally sensitivity analyses are conducted on the capacity pooling distance and the holding costs to derive further insights.

4.5.1 Experimental setting

Table 4.3 summarizes the characteristics of the considered instances: number of access hub locations, number of local cells, and area and population covered by the network. 100 non-stationary demand scenarios are generated randomly from given distributions at the hourly level with monthly, weekly, daily and hourly seasonality factors. Figure 4.7 illustrates demand dynamics by displaying access hub volume requirements box plots and snapshots of demand levels in two consecutive tactical periods as seen in Figure 4.2 for a sample local cell from instance E. The number of scenarios is chosen to ensure tactical decision stability with a reasonable in-sample statistical gap (1.5%) and coefficient of variation (0.5%) as detailed in B. The considered planning horizon spread over two months, with 8 weekly tactical periods and hourly operational period. Each week is composed of seven days of ten operating hours each. The ϵ-method is implemented with a guaranteed optimality gap of 0.1%.

Table 4.3: Experimental Instances

Instance	Access hubs	Local cells	Area covered (sq.km)	Population covered
A	39	1	24.2	338,000
B	54	2	42.1	590,000
C	138	4	66	924,000
D	421	10	178.4	2,500,000
E	838	20	410	5,740,000

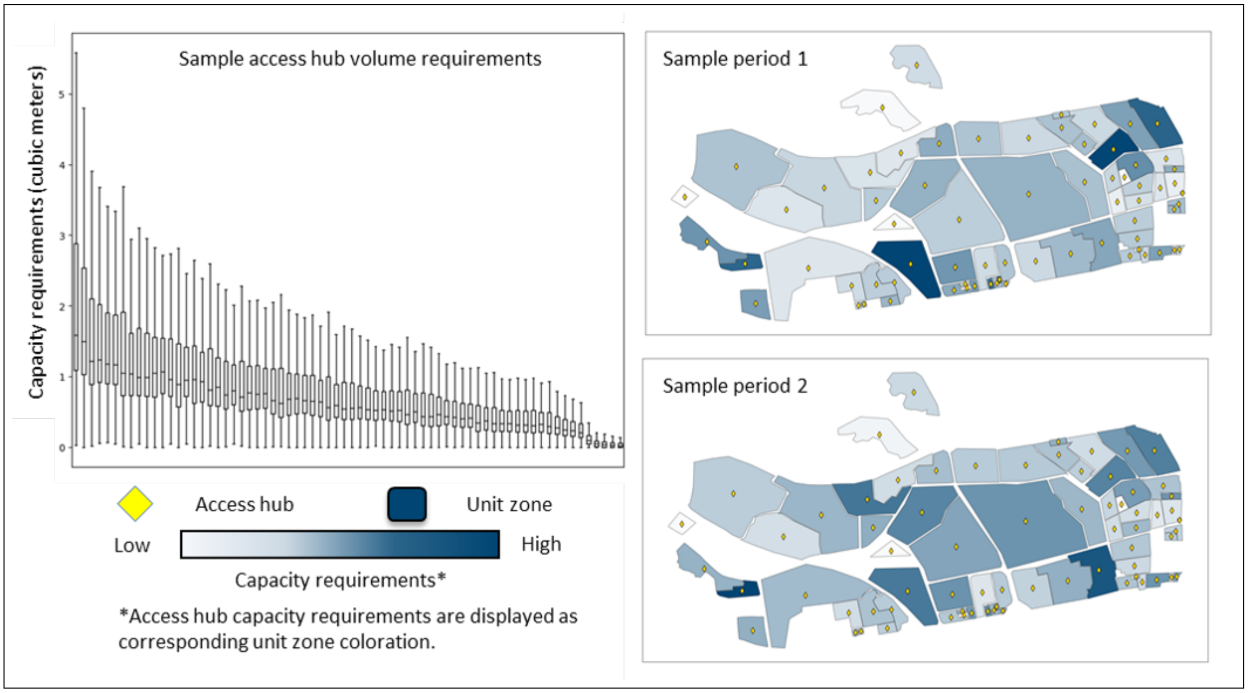

Figure 4.7: Demand Dynamics Sample for a Local Cell

As benchmark solutions, static capacity deployments are considered for each instance. Such static capacity deployment represents the minimum capacity module deployment required over the network of access hub locations to satisfy storage requirements for all operational periods within the planning horizon T without being able to update capacity over time or use capacity pooling recourse actions. Benchmark solutions are found by solving $\min\{\sum_{t \in T} \sum_{l \in \mathcal{L} \cup \mathcal{W}} h_l S_l(t)\}$ such that $S_l(t) \in \{vS_l(t) \geq D_l(\tau, \omega), \forall l \in L, \tau \in T_t, t \in T, \omega \in \Omega\}$ over the entire planning horizon with no relocation or recourse by relaxing spatial constraints to ensure feasibility.

An instance has more or less savings potential depending on its demand dynamics and network configuration. Although assessing the potential of capacity pooling a priori is non trivial, the potential of capacity relocation can be assessed by a lower bound to the dynamic capacity deployment problem with no capacity pooling. Define $\tilde{S}_l(t)$ as the maximum number of capacity modules required at location l in any operational period associated with tactical period t in all considered scenarios; that is $\tilde{S}_l(t) = max(\lceil D_l(\tau,\omega)/v \rceil, \forall \tau \in T_t, \omega \in \Omega)$. Then, an instance's capacity relocation cost savings potential can be computed by factoring in holding costs while ignoring relocation costs, producing a lower bound for the dynamic capacity deployment problem with no capacity pooling, with objective value $\sum_{t \in T} h_l \tilde{S}_l(t)$. Benchmark solutions and relocation potential for the considered instances are summarized in Table 4.4.

Table 4.4: Benchmark Solutions and Relocation Potential

Instance	Total cost	Capacity	Potential cost savings
A	\$138,966	189	7.93%
B	\$181,275	245	8.72%
C	\$453,137	618	7.58%
D	\$1,325,490	1820	7.29%
E	\$2,840,510	3818	9.25%

The initial capacity deployment is defined by running the proposed solution approach for the tactical period immediately preceding the studied planning horizon by relaxing constraint (4.16). The default values of input parameters are estimated relying on company experts and presented in B. Each instance is assigned one depot in one of its local hub locations to store unused capacity modules at no cost. The number of modules available I_0 and the penalty cost p_l are set to large values (respectively 5000 modules and \$100,000 per modules in order to prevent full recourse actions by lack of capacity and focus on feasible capacity deployments with capacity pooling. As suggested by [92] (through simulation) when studying a french parcel express company, this chapter considers the value of the k constants to be 0.82 for riders and 1.15 for couriers.

All experiments were implemented in Python 3.7 using Gurobi 9.0 as the solver and were computed using 40 logical processors on an AMD EPYC Processor @ 2.5GHz.

4.5.2 Computational Performance

The experiments presented in this section study the computational performance of the proposed solution approach when tackling instances of different sizes. The first experiment aims at validating the efficiency of the proposed acceleration methods in section (4.4.2) for the Benders algorithm. It examines the impact of combinations of the acceleration methods on the runtime of the Benders algorithm for solving the optimization model (4.15-4.25) for one relocation period with no lookahead. Figure 4.8 display the runtimes for instances C with a capacity pooling distance of 1km and a time cutoff of 15 hours; B represents the original Benders algorithm developed in section (4.4.1); BP represents Benders with pareto-optimal cuts; BE represents Benders with the ϵ-optimal method; and BPE represents BP with the ϵ-optimal method.

Figure 4.8 suggests that pareto-optimal cuts have the strongest impact on computational performance as it allows the BP algorithm to converge in 965 seconds when the B algorithm did not converge within the time limit. The ϵ-optimal method suggests a significant improvement compared to the original Benders algorithm, and has an advantage over BP when close to optimality (while guaranteeing a solution within 0.1% of optimality). Similar behaviors can be observed for larger instances, with BPE outperforming B, BP and BE.

Next, Figure 4.9 depicts the computational performance of the proposed solution approach for different lookahead values as a function of network size. Each data point is the average runtime per period for a minimum sample set of 16 instances (8 relocation periods times 2 capacity pooling distances) and a maximum of 48 instances (8 relocation periods times 6 capacity pooling distances) based on the other experiments presented in the chapter. The first observation is that the proposed solution approach is efficient in solving large-scale instances considered in this chapter (838 access hubs), with a maximum runtime around 3 hours (with 2 weeks lookahead); this result suggests tractability

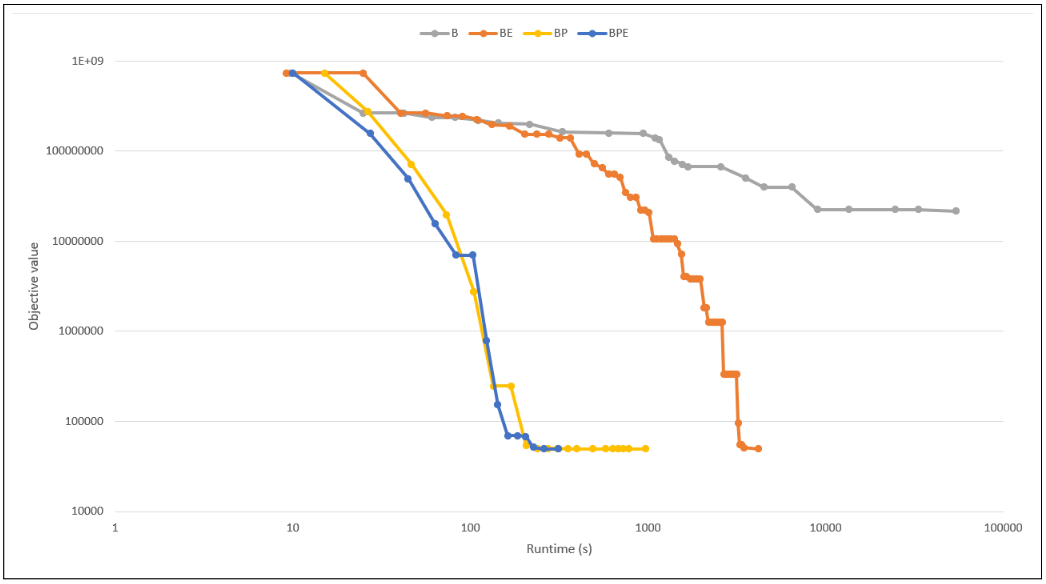

Figure 4.8: Benders Algorithm Improvements Comparison on Instance C

for most urban area sizes, including megacities. The second observation is that adding tactical lookahead reasonably increase runtime: 1 week and 2 weeks lookahead runtimes are respectively at most 2.1 times and 3.5 times as long as no lookahead runtimes wihtin the range of network sizes considered.

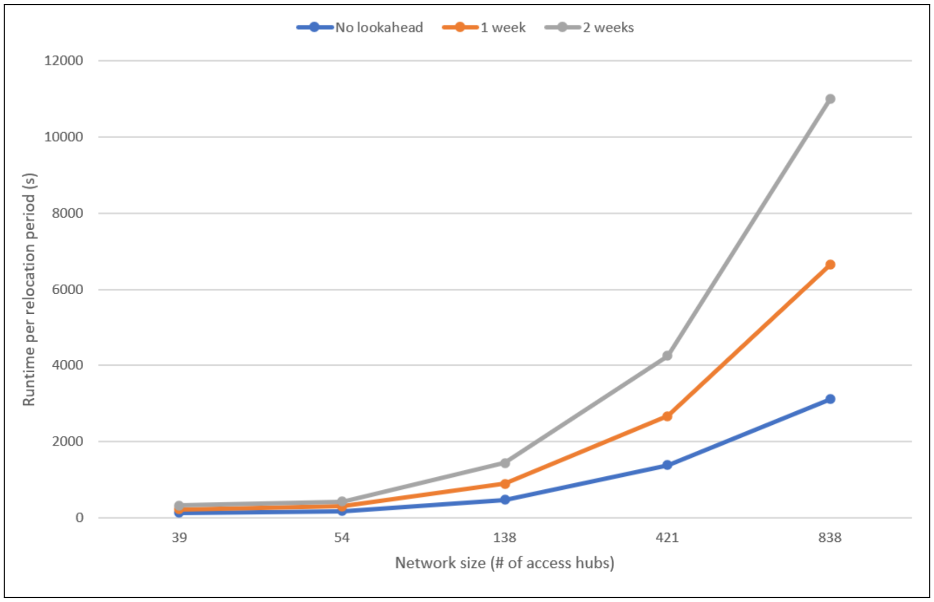

Figure 4.9: Computational Performance for Different Lookahead Values as a Function of Network Size

4.5.3 Comparative Results

The results presented in this section highlight the benefits of relocating capacity dynamically over time and allowing capacity pooling compared to a static capacity deployment with no capacity pooling. Results are summarized in Table 4.5 for different lookahead values and capacity pooling distance (in km). Table 4.5 presents total costs of the network, deployed capacity (maximum number of modules), relocation share (average number of relocations per period as a share of capacity), and cost and capacity savings with respect to the static counterpart.

First, cost and capacity savings are observed in all the instances. Maximum cost savings of 28.3% and capacity savings of 26.46% are reached for instance A with a capacity pooling distance of 2km and a 2 weeks tactical lookahead. Most of these savings are a result of the capacity pooling recourse as savings with capacity pooling of 0km indicate a much lower savings (maximum of 6.26% cost savings). Note that for each instance,

Table 4.5: Results Highlights and Comparison with Static Capacity Deployments

Instance	Pooling distance	Lookahead (θ)	Total cost	Capacity	Relocation share	Cost savings	Capacity savings
A	0	0	$131,333	183	7.31%	5.49%	3.17%
		1	$130,269	187	4.88%	6.26%	1.06%
		2	$130,083	184	4.82%	6.39%	2.65%
	2	0	$100,925	139	7.19%	27.37%	26.46%
		1	$99,779	139	6.47%	28.20%	26.46%
		2	$99,644	139	6.03%	28.30%	26.46%
B	0	0	$170,189	237	6.86%	6.12%	3.27%
		1	$169,940	239	6.64%	6.25%	2.45%
		2	$169,174	239	6.33%	6.68%	2.45%
	2	0	$140,470	195	6.60%	22.51%	20.41%
		1	$138,847	195	6.15%	23.41%	20.41%
		2	$138,841	195	6.15%	23.41%	20.41%
C	0	0	$429,967	594	6.29%	5.11%	3.88%
		1	$428,683	595	6.11%	5.40%	3.72%
		2	$428,544	595	5.95%	5.43%	3.72%
	2	0	$400,482	548	6.20%	11.62%	11.33%
		1	$396,944	550	5.64%	12.40%	11.00%
		2	$396,776	550	5.59%	12.44%	11.00%
D	0	0	$1,263,680	1746	7.01%	4.66%	4.07%
		1	$1,255,070	1747	6.18%	5.31%	4.01%
		2	$1,249,130	1737	6.02%	5.76%	4.56%
	2	0	$1,228,360	1698	6.39%	7.33%	6.70%
		1	$1,219,230	1699	6.02%	8.02%	6.65%
		2	$1,219,050	1696	6.01%	8.03%	6.81%
E	0	0	$2,646,090	3632	7.00%	6.84%	4.87%
		1	$2,624,860	3626	6.52%	7.59%	5.03%
		2	$2,624,380	3626	6.51%	7.61%	5.03%
	2	0	$2,614,330	3587	6.93%	7.96%	6.05%
		1	$2,596,690	3587	6.55%	8.58%	6.05%
		2	$2,595,550	3589	6.53%	8.62%	6.00%

savings with no capacity pooling are less than potential savings presented in Table 4.4 (where relocation costs are not accounted for). The average number of relocations per period represent up to 7.31% of the capacity, and is decreasing as more tactical lookahead is added; capacity deployments are gradually reconfiguring networks. Capacity savings indicate that the total number of modules required (both deployed and stored at a depot) is inferior to the number of modules required in static counterparts. Capacity savings also increase as capacity pooling is available, making the total capital invested in capacity modules inferior than in static counterparts.

Furthermore, the results show that adding tactical lookahead is beneficial for all instances with and without capacity pooling by improving cost savings and decreasing the number of relocations. The role of tactical lookahead is to anticipate future needs and avoid relocations that will be reverted to in the future. Lookahead can be seen as the flexibility hedging of the solution approach to avoid relocations under uncertainty. However, the difference between one week and two weeks of tactical lookahead is more subtle with smaller cost improvements. These results suggest that solution's quality increase with lookahead (θ), offering extra cost savings. Tactical lookahead anticipates for future relocations therefore decreasing relocation share at the cost of slightly higher capacity deployments. However, there does not seem to be significant improvements from extending the lookahead from one week to two weeks, especially when considering the additional computational runtime.

Lastly, capacity pooling brings significant value to instance A, B, and C, but less cost savings improvements for instance D and E. This is probably due to the the fact that instances D and E have lower hub density, increasing the distance between access hubs (see Table 4.3). Section 4.5.4 examine the impact of capacity pooling distance in more details by focusing on instance C.

4.5.4 Capacity Pooling Variations

This experiment examines the effect of capacity pooling as a way to further decrease costs. Table 4.6 summarizes the effect of different capacity pooling distances (in km) on instance C's solutions. It presents average additional rider and courier travel (induced by detours), and cost and capacity savings for instance C. Figure 4.10 displays a plot of cost and capacity savings as a function of pooling distance.

The increase in capacity pooling distance allows to produce superior solutions but only until a maximum of 12.55% is reached with a pooling distance of 5km. This trend can clearly be seen in Figure 4.10. Indeed, no matter how large capacity pooling pooling neighborhoods are, constraints (4.13) and (4.14) limit capacity poolings from an operational point of view: riders and couriers cannot perform long distance detours as it would

Table 4.6: Sensitivity Analysis on Capacity Pooling Distance for Instance C ($\theta = 1$)

Pooling distance	Rider travel	Courier travel	Cost savings	Capacity savings
0	0.00	0.00	5.40%	3.72%
0.5	0.35	4.59	9.67%	8.41%
1	0.49	9.86	12.12%	10.68%
2	0.48	9.71	12.40%	11.00%
5	0.48	9.71	12.53%	11.00%
10	0.48	9.71	12.51%	11.17%

disrupt their activity by delaying other pickup / deliveries. Table 4.5.4 shows that most of the additional travel induced by detours is performed by couriers; since riders have larger carrying capacity, one rider detour may require multiple courier detours. Note also that since couriers are often using lightweight vehicles (if any vehicles at all), long distance detours may not be practical which may also limit the capacity pooling distance from a design perspective. The same behavior can be observed for the other instances.

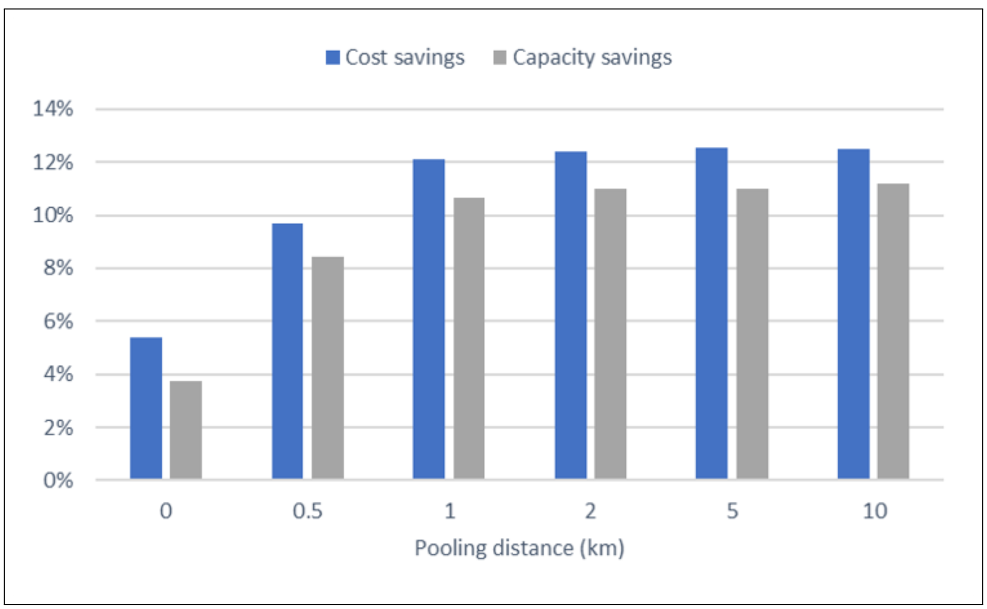

Figure 4.10: Cost and Capacity Savings as a Function of Pooling Distance

4.5.5 Holding Costs Versus Relocation Costs

This experiment examines the influence of relocation costs and holding costs on dynamic capacity deployments. Intuitively, two extreme cases can be identified: (1) if holding costs are negligible compared to relocation costs, there is no incentive to dynamically adjust capacity, and (2) if relocation costs are negligible compared to holding costs, a myopic view of the problem would be optimal as anticipating future relocations does not save cost. Apart from extreme cases, variations of holding costs and relocation cost can represent different urban environments. A very dense city may have high holding costs (prime real estate) and low relocation costs (short distances between locations). In this experiment, four cases are examined: High-high, High-low, Low-high and Low-low, where High and high respectively represent high holding costs and high relocation costs and Low and low respectively represent low holding costs and low relocation costs. Cost vectors are scaled linearly and high costs are chosen to be 100% higher than baseline values while low costs are assumed to be 50% lower than baseline values. Table 4.7 presents total cost, capacity (maximum number of modules deployed), relocations, relocation share (average number of relocations per period as a share of capacity), and cost and capacity savings for instance C with a capacity pooling distance of 2km. Savings are computed comparing to benchmark solutions with corresponding cost adjustements (holding costs).

Table 4.7: Impact of Holding versus Relocation Costs on Instance C

Case	Relocation share	Cost savings	Capacity savings
High-low	6.12%	13.07%	9.62%
High-high	5.22%	11.76%	9.78%
Low-low	6.20%	13.10%	8.13%
Low-high	3.73%	9.02%	7.79%

A first observation is that cases where relocation costs are low perform best with costs savings around 13.1%, regardless of holding costs. When relocation costs are high, cost savings are worse, especially when holding costs are low (9.02%). Low holding cost cases deploy more capacity modules overall which impact capacity savings, but are still able to reach high cost savings when relocation costs are low. The combination of low holding costs and high relocation costs decreases opportunities for worthy relocations (only 3.73% relocation share), requiring more capacity deployed and therefore limiting cost savings (9.02%). Similar behavior can be observed on the other instances.
Overall, this experiment indicates that denser urban environment (high holding costs) tend to be better candidates for dynamic capacity management of access hub networks. Moreover, low relocation costs (i.e. easy installation and good mobility of capacity modules) can make any urban environment a worthy candidate for such capacity management strategy. Finally, the combination of lesser dense urban environment and high relocation costs significantly limits opportunity for cost savings.

4.6 Conclusion

This chapter defines and formulates the Dynamic Pooled Capacity Deployment Problem in the context of urban parcel logistics. This problem involves a tactical decision on the relocation of capacity modules over a network of discrete locations associated with stochastic demand requirements. To improve the quality of the capacity deployment decisions, the proposed model integrates an estimate of the difference of operations cost, which includes capacity assignment decisions with the possibility of capacity pooling between neighboring locations. It also integrates synchronization requirements of the 2-echelon routing subproblems, using an analytical derivate from the route length estimation function. The dynamic problem is modeled and approximated with a two-stage stochastic program with recourse, where all capacity deployment decisions on a finite planning horizon are moved to the first stage. Due to the uncertainty of capacity requirements and the challenges of solving the MIP formulation for realistic networks of several hundreds locations, a roll-out approach with lookahead based on a Benders decomposition of the finite planning horizon problem coupled with acceleration methods is proposed. Five instances of networks of different sizes are presented to perform computational experiments to test the performance of the proposed approach and assess the potential of the defined capacity deployment strategy.

Results show that the proposed approach produces solutions in a reasonable time even for large scale instances of up to 838 hubs. They suggest that a dynamic capacity deployment strategy with capacity pooling has a significant advantage over a static capacity deployment strategy for access hub networks, with up to 28% cost savings and 26% capacity savings. Results also show that one-week lookahead helps producing superior solutions by anticipating future relocations, but adding a two-weeks lookahead does not make a significant improvement. Increasing the capacity pooling distance, while increasing computing time, tend to increase opportunities for cost savings by allowing more locations to pool capacity until an operational feasibility threshold is reached. Dynamically adjusting workforce assignment in the network was not explored but could potentially overcome this limitation. Denser urban environments (i.e. with higher real estate costs) are natural candidates for dynamic capacity deployments as relocation costs are more easily overcome by holding costs. However, relocation costs are the most limiting when it comes to cost savings. Technology solutions featuring cheaper installation costs and high degree of mobility make it more interesting to consider periodic network reconfigurations.

The implementation of such innovation also has management challenges not studied in this chapter. For instance, implementation may require a more agile workforce, specialized training and targeted hiring enabling a data-driven approach to managing network capacity. Management challenges also need to be considered by decision makers along with the potential reduction of fixed-assets offered by capacity savings when evaluating the solution for implementation.

Finally, there are numerous research avenues around reconfigurable networks, dynamic capacity management and access hubs in urban parcel logistics. Where technology allows for very frequent network reconfiguration, solutions featuring not only modular but mobile capacity (e.g. on wheels) and near real-time capacity relocation can become relevant as a complement to the proposed dynamic capacity deployment strategy. Moreover, the possibility of updating operations planning as needed (e.g. dynamic routing, dynamic staffing) can unlock the potential of capacity pooling not only as a recourse but as an integral part of network design and operations planning.

CHAPTER 5

MOBILE ACCESS HUB DEPLOYMENT FOR URBAN PARCEL LOGISTICS

In this chapter, we examine the potential of mobile access hub deployments for urban parcel logistics by identifying the impact of design parameters on economic and environmental performance. We propose a mathematical modeling framework and an integer program to assess the performance of mobile access hub deployments, and study the impact of a set of design parameters through synthetic cases and an illustrative case inspired from a large parcel express carrier's operations. Results indicate design flexibility relative to the location of hubs and pronounced advantages in highly variable environments. The illustrative case shows significant savings potential in terms of cost and time efficiency as well as environmental sustainability. It emphasizes a trade-off between operational efficiency and environmental sustainability that can be balanced to achieve global sustainability goals while being economically sound.

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5.1 Introduction

Urban parcel logistics play an important role in the development of the economy as it represents an essential enabler for e-commerce, but also create externalities such as traffic congestion, air pollution, and nuisances to the population. Additionally, last-mile logistics in urban areas represent up to 28% of distribution costs [132] and is considered to be the least efficient transportation leg [133]. Global urbanization, which is predicted to reach 68% by 2050 [37], and the fast growth of e-commerce (20% annually on the 2017-2019 period [83]) contribute to an ever growing demand for urban parcel logistics services, motivating the search for sustainable innovations in city logistics (e.g. [5] and [134]). These trends have been accelerated due to attempts to mitigate the impacts of the COVID-19 pandemic (e.g., sequestering in place), requiring companies to increase their last-mile delivery capabilities and to deal with the dramatic shift to online channels [85].

In highly populated and dense urban areas, the development of transportation infrastructure can be difficult due to limited availability of suitable locations for logistic activities and costly (e.g. high real estate costs). Additionally, in an effort to promote the mitigation of negative externalities induced by urban transportation, local governments have started implementing several types of restriction policies such as limiting access of certain freight vehicles to city centers [135]. As a result, considerable research efforts have been put towards designing innovative and flexible freight systems to accommodate for various distribution needs and the challenges of sustainable urban development (see [136] for examples of innovations). Several of these initiatives require the use of lightweight commercial vehicles to perform pickup and delivery services, and often result in an increase in number of trips due to decreasing vehicle capacity. As a remedy, a thread of research examines the combination of micro consolidation and transshipment hubs and light-weight commercial vehicles such as cargo-bikes to perform pickup and delivery services in dense urban areas as a way to design cost effective and sustainable last-mile operations [137]. These hubs can be designed to be mobile to cope with the difficulty of securing real estate and to add network design flexibility by enabling a dynamic use of urban space for logistics purposes. A few experiments regarding the use of mobile hubs for urban parcel logistics can be found in the literature such as the STRAIGHTSOL [35] project.

Mobile access hubs are mobile logistics facilities which partially constitute dynamic capillary logistics networks in the context of Physical Internet enabled hyperconnected urban parcel logistics [81]. Capillary logistics networks enable first-and-last mile logistics and fulfillment activities and customer interfaces with logistics systems by providing, for instance, sites (e.g. mobile facilities) where logistics activities can take place (e.g. transshipment of goods). Mobile access hubs offer consolidation and transshipment points between different types of vehicles at the neighborhood level (see [81] for more details on access hubs). They can materialize in different ways such as modified trailers, commercial vans, or AGV lockers, and are deployed for a short-term period of time in a public or private location. Figure 5.1 illustrates two examples of mobile access hubs from industry where modified trailers are temporarily located in a reserved parking space in the city center. Without mobile access hubs, a courier performs the following cycle of work several times in a single day: load parcels for delivery at a local hub (e.g. urban consolidation center) located away from the demand zone, drive to the demand zone to perform deliveries and pickups, and return to the local hub. With mobile access hubs, such cycles originate and terminate at a mobile access hub located close to the demand zone, reducing the couriers' travel and leveraging consolidation opportunities by using larger vehicles to transship goods between the local hub and the mobile access hub.

Figure 5.1: Examples of Mobile Access Hubs (Left: TNT Pilot in Brussels, Belgium [89]; Right: UPS Pilot in Berlin, Germany [86])

This chapter contributes to the academic literature by expanding the understanding of characteristics influencing the economic and environmental efficiency of mobile access hub deployments. In particular, it proposes a mathematical modeling framework and examines the potential of mobile access hub deployment for urban parcel logistics by identifying the impact of design parameters on economic and environmental performance using synthetic examples and an illustrative case inspired from a large parcel express carrier's operations. Section 5.2 summarizes advances in the academic literature regarding the use of mobile hubs in urban logistics. Section 5.3 describes the studied problem and the modeling framework used to design and assess the performance of mobile access hub deployments. Section 5.4 reports on a set of experiments and results regarding the deployment of a single mobile access hub, the deployment of a mobile access hub fleet in a synthetic urban area, and the deployment of a mobile access hub fleet in an illustrative urban area inspired from a large parcel express carrier's operations. Finally, section 5.5 highlights key takeaways and managerial insights, and identifies promising research avenues.

5.2 Literature Review

The impact of city logistics on sustainability and liveability of cities has recently gained a lot of attention from the academic literature (see [138] for a recent literature review on city logistics research). More and more cities are implementing urban traffic restrictions (e.g. time-access restrictions and vehicle restrictions) to fight the negative externalities of logistics activities such as traffic congestion and air pollution and improve social sustainability. However, the positive impact of such restrictions on liveability and attractiveness of city centers often comes at the expense of environmental sustainability as reported in [139]. A thread of research on last-mile logistic systems using micro-consolidation centers and light-weight vehicles such as small electric vehicles and cargo bikes (e.g. [140, 141]) has emerged to deal with such restrictions while fostering cost efficient and sustainable logistics operations in dense urban areas. [137] reports on a set of initiatives implementing smaller and lighter vehicles in urban areas by providing a literature review on sustainable vehicle-based alternatives in last-mile logistics, and highlight the need to explore innovative solutions to mitigate the increase of the number of trips and induced negative externalities due to decreasing vehicle capacity.

Access hubs serve as consolidation and transshipment points between first-and-last-mile logistics activities and inbound and outbound activities. Access hubs are typically located at the neighborhood level shaping the capillary part of multi-echelon hyperconnected parcel logistics networks [81]. Multi-echelon networks for urban distribution have received a lot of attention in the academic literature (e.g. [142], [30], [98], [143], [99], [144]), often using urban consolidation centers (UCC) or urban distribution centers (UDC) to bundle goods outside the boundaries of urban areas. As reported in [29], several micro-consolidation initiatives have been proposed to downscale the consolidation effort by bundling goods at the neighborhood level using capillary networks of hubs located much closer to pickup and delivery points, defined as access hubs in the conceptual framework proposed by [81]. Examples of such initiatives are satellite platforms (e.g. [30]), micro-consolidation centers (e.g. [31]), mobile depots (e.g. [32]), micro-depots (e.g. [33]), and urban transshipment points (e.g. [145]).

Several field studies have been conducted in European cities suggesting significant potential (e.g. 20% travel savings and 54% CO_2 equivalent savings [146]) but failed to generalize key learnings and insights, making it a challenge for both private and institutional actors to replicate implementations and making transferability a key issue in the urban freight transport research [29].

While [140] reported clear environmental improvement from the use of micro-depots and electric assisted tricycles in an urban area with access restrictions in Barcelona, the economic aspect was not as potent. The combination of demand dynamics and real estate availability and price in dense urban areas makes the implementation of logistics hubs in certain neighborhoods economically infeasible, not without mentioning the potential roadblocks from locals perceiving logistics activities as a potential nuisance.

Mobile hubs as examined by [35], [102] and [32]) appear to be potential solutions with flexibility and robustness as foreseeable benefits [147]. All [35], [102] and [32] examined the use of single mobile hub per region with implementation test cases respectively in Brussels, Gothenburg and Rio de Janeiro. While [35] and [102] are reporting on the results of the case study, [32] were able to develop a method to assess the economic and environmental viability of mobile hub setups in different neighborhoods based on their expected delivery loads using Monte Carlo simulation. [145] also proposed an impact assessment model using routing approximations to evaluate the performance of urban distribution systems combining cargo bikes and access hubs; the authors provided a framework to assess different network combinations to give recommendations on where to locate access hubs limited to a few options, and did not consider the full potential of mobility by allowing hubs to be dynamically located (e.g. daily). This chapter extends on the work presented in [32] and in [145] and identifies the impact of both demand and design characteristics on the economic, environmental and time efficiency of the deployment of a mobile access hub fleet in the context of urban parcel logistics.

5.3 Problem Description and Modeling

In this section, the examined mobile access hub deployment problem is described along with a mathematical modeling framework developed to assess the economic, time efficiency and environmental performance of deployments. First, we define the studied problem and formulate it as an optimization challenge. Then, we present a set of key performance indicators. Finally, we develop an operations modeling framework and an integer program to provide solutions to the defined problem and assess their performance in terms of the set of key performance indicators.

5.3.1 Problem Description

A parcel express company provides pickup and delivery services to customers in an urban territory, here referred as local cell, composed of a set of unit zones. The company is operating a logistics hub located near the boundary of the local cell, called local hub, serving as urban consolidation center for every unit zone composing the cell. Each unit zone represent a demand area where couriers perform pickup and delivery services. The couriers develop experts knowledge of their assigned unit zones notably in terms of geography and customer base. Parcels can be moved between customer locations and the local hub in two ways: (1) couriers travel back and forth between their respective unit zones where they perform pickup and delivery tours on light-weight vehicles (e.g. cargo motorcycle) and the local hub, or (2) couriers travel back and forth between their respective unit zone and a nearby mobile access hub where parcels are temporarily stored until a rider transships them between the mobile access hub and the local hub with a larger vehicle (e.g. commercial van). In order to provide timely services, a maximum transit time is to be ensured. The maximum transit time is defined as the maximum in-transit duration of a parcel moving from a local hub to a customer or vice-versa. The objective of the company is to minimize operations costs within the local cell by using a number of mobile access hubs, while ensuring a maximum transit time θ between the local hub and customer locations.

A number of mobile access hubs, say M, is available for deployment every morning at the local hub, and can be located in a set of discrete parking locations throughout the local cell, each location being able to serve one or more nearby unit zones. In the context of this chapter, the following assumptions are made:

- Mobile access hub candidate locations are known and can be reserved for a fixed price at the beginning of each day
- Unit zones are to be served by at most one mobile access hub at the time
- Mobile access hubs can be stored nearby their local hub if not deployed
- Mobile access hubs are big enough to hold the load of parcels of their assigned unit zone(s)
- Mobile access hubs are to be replenished by out-and-back rider trips

Finding space to park a trailer-like mobile access hub in a dense city center can be challenging, and require ground work to identify and secure such candidate location (e.g. reserved commercial parking area). Uncertainty about the availability of such space (e.g. due to competing reservation requests) is not considered in the context of this chapter.

Although unit zones could make use of several access hubs at the same time, the choice is made to limit the assignment of a unit zone to a unique mobile access hub. This design choice aims at making routing more straightforward, especially when the location of the one mobile access hub may differ every day. For similar reasons, the choice is made to limit the assignment of unit zones to mobile access hubs to once a day (at the time of deployment).

When mobile access hubs are not deployed to serve unit zones, it is assumed that they can be stored nearby the local hub. In some cases (e.g. local hub located in a high-density area), mobile access hubs could have to be stored further away from the local cell, which would induce an additional deployment cost not modeled in this chapter.

The use of standard mobile access hub technology solutions (e.g. modified trailers like in Figure 5.1) may provide enough storage capacity to make the problem uncapacitated as long as mobile access hubs are not assigned to too many adjacent unit zones (i.e. do not handle too much parcel flow) and have frequent rider and courier visits.

The restriction to out-and-back rider visits limits the routing complexity of dynamic hub locations and is a conservative assumption when evaluating the performance of mobile access hub deployments.

Let Z be a set of unit zones served by local hub l, and A a set of candidate locations where a fleet of M mobile access hubs can be deployed. A mobile access hub deployed in location $a \in A$ serves unit zones $z \in Z(a) \subseteq Z$. A mobile access hub deployment is represented by a vector $x = (x_a, \forall a \in A)$, where x_a is the binary assignment of a mobile access hub in location a. In each unit zone z, the number of pickup and delivery requests performed (i.e. customer visits) during the day is expressed as a number of stops n_z. The economic optimization challenge can then be formulated as follow:

$$min_{x \in X} \left\{ C^D(x) + \mathbb{E}\left[C^R(x, \sum_{z \in Z} n_z) + \sum_{z \in Z} C_z^C(x, n_z) \right] \right\} \tag{5.1}$$

Where X represents the set of feasible deployments, $C^D(x)$ represents the cost of deploying mobile access hubs according to vector x, $C^R(x, \sum_{z \in Z} n_z)$ represents the operations cost of riders moving parcels between the local hub and mobile access hubs locations and $C_z^C(x, n_z)$ represents the operations cost of couriers performing pickups and deliveries within unit zone z. Operations are planned to satisfy an maximum transit time θ between the local hub and customer locations, which is to be reflected in operations costs.

5.3.2 Performance Indicators

In this section, a set of key performance indicators summarized in Table 5.1 is proposed for the assessment of mobile access hub operations versus traditional operations divided along the economic, time efficiency and environmental assessments.

Table 5.1: Performance Indicators

Assessment	Performance indicator
Economic	Total cost Cost per parcel
Time efficiency	Transportation time per parcel Average time between customers
Environmental	Greenhouse gas emissions Travel distance per parcel

Economic Assessment

The economic assessment of mobile access hub operations can be done globally, by computing the total system cost (i.e. deployment cost and operations cost) as in optimization challenge (5.1). That is, by computing the sum of the cost of deploying mobile access hubs and the cost of rider and courier operations (vehicle and driver costs) necessary to perform pickup and delivery services. Additionally, the total system cost can be divided by the number of parcels handled (i.e. pickups and deliveries) to obtain a cost per parcel useful when assessing the economic impact of last-mile logistics on landed costs and compare the economic viability of instances of instances with different demand volumes.

Time Efficiency Assessment

From an operational perspective, the transportation time per parcel gives an indication on time efficiency of workers operating in the system. It is defined as the total vehicle travel time divided by the number of parcels handled. More specifically, courier productivity can be assessed by the average time between customer locations on a courier route (i.e. the ratio of courier operations time by the number of parcels handled). This is particularly important from a managerial perspective as couriers daily activities are significantly modified when using mobile access hubs (e.g. their reference logistics hub may change from one day to another). Getting couriers onboard is critical to the sustainable implementation success of mobile access hubs, and productivity gain can be a convincing factor (especially if couriers are partially paid based on the number of parcels picked up or delivered).

Environmental Assessment

The environmental footprint of mobile access hub operations is composed of direct impact (i.e. riders and couriers vehicle operations) and negative externalities (such as induced traffic congestion due to vehicle movement and pickup and delivery stops). A common metric for assessing direct environmental impact is greenhouse gas emissions from vehicle movement computed as the total travel distance times an emissions factor for each type of vehicle. Rider vehicles are typically larger (e.g. package car, delivery van), faster and a bigger source of pollutants than courier vehicles designed to be convenient and respectful in dense city centers (e.g. tricycle, electric motorcycle). While externalities are complex to model and assess, the distance travelled per parcel gives an indication on routing efficiency; a shorter distance travelled per parcel is more likely to limit externalities by reducing the travel footprint of operations in a area (see [148] for more details on assessing negative externalities from transportation metrics).

5.3.3 Operations Modeling

The mobile access hub deployment problem is a tactical problem from which decisions directly impact urban parcel logistics operations. While explicitly modeling operations is not necessary to inform a tactical decision, this section proposes a set of continuous approximations to assess the economic, environmental and time efficiency of mobile access hub operations. As indicated in [149], using such continuous approximations are appropriate to address high-level system performance because they are parsimonious, tractable and yet realistic and are useful to capture operations complexity and take informed decisions (see [93] for a review on the development of such models for logistics and transportation systems).

Pickup and Delivery Routes

With or without the use of mobile access hubs, a set of couriers is to execute pickup and delivery routes visiting customers located in unit zones from either a local hub or a mobile access hub. The starting point of the proposed operations modeling is the approximation of the vehicle routing problem via route length estimations proposed by [118]. In the case of couriers performing n stops in unit zone z from a hub, say h, the total distance traveled can be expressed as the combination of a stem distance (from the originating hub to the area of service) and a in-tour distance (in the area of service) as follows:

$$D_z(n_z, h) = 2d_{hz}\frac{n_z}{Q_z^h} + n_z k(\delta_z)^{-\frac{1}{2}} \tag{5.2}$$

Where d_{hz} is the average distance between the originating hub h and unit zone z, n_z is the number of stops to perform in unit zone z, Q_z^h is the length or routes of couriers operating in unit zone z from hub h and δ_z the density of customer locations in unit zones z. k is a constant related to the distance metric used that can be computed by simulation [119]. Similarly, the total time required to perform courier routes can be expressed as follows:

$$T_z(n_z, h) = \frac{n_z}{Q_z^h}\left(t_{fixed}^{courier} + \frac{2d_{hz}}{s_0^{courier}}\right) + n_z\left(\frac{k(\delta_z)^{-\frac{1}{2}})}{s^{courier}} + t_{stop}^{courier}\right) + n_z v t_{handling}^{courier} \tag{5.3}$$

Where $t_{fixed}^{courier}$, $t_{stop}^{courier}$ and $t_{handling}^{courier}$ are respectively the couriers fixed time for each route (start and end of a route), the stopping time at each customer location and handling time per unit, $s_0^{courier}$ and $s^{courier}$ are respectively the couriers stem and in-tour speed, and v the average number of units handled per stop (pickup or delivery). Finally, the induced operations cost can be approximated as follows:

$$C_z(n_z, h) = \frac{n_z}{Q_z^h}\left(c_{fixed}^{courier} + 2d_{hz}c_0^{courier}\right) + n_z k(\delta_z)^{-\frac{1}{2}} c^{courier} + T_z(n_z, h)c_{wage}^{courier} \tag{5.4}$$

where $c_{fixed}^{courier}$, $c_0^{courier}$, $c^{courier}$, and $c_{wage}^{courier}$ are respectively the couriers 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. \$/h).

Baseline Operations and Transit Time

In the baseline case, couriers are operating from a local hub without mobile access hub transshipment. That is, operations travel, time and cost can directly be computed with $D_z(n_z, l)$, $T_z(n_z, l)$, and $C_z(n_z, l)$. Moreover, the maximum transit time between local hub l and a customer location in zone z is symmetrical for inbound (from customer to local hub) and outbound (from hub to customer) operations and can be computed as the time a courier takes to move from the local hub to the last stop on its route and can be approximated as follows:

$$T_{lz}^{transitIB} = T_{lz}^{transitOB} = \frac{1}{2}t_{fixed}^{courier} + \frac{d_{lz}}{s_0^{courier}} + Q_z^l\left(\frac{k(\delta_z)^{-\frac{1}{2}}}{s^{courier}} + t_{stop}^{courier}\right) + Q_z^l v t_{handling}^{courier} \tag{5.5}$$

Where Q_z^l is the number of stops on a single courier route leaving from local hub l, which can be adjusted as long as it is inferior or equal to a courier's capacity $\bar{Q}$ expressed in number of stops. Therefore, to satisfy $T_{lz}^{transitIB} = T_{lz}^{transitOB} \leq \theta$, Q_z^l must satisfy:

$$1 \leq Q_z^l \leq \frac{\theta - \frac{1}{2}t_{fixed}^{courier} + \frac{d_{lz}}{s_0^{courier}}}{\frac{k(\delta_z)^{-\frac{1}{2}}}{s^{courier}} + t_{stop}^{courier} + v t_{handling}^{courier}} \tag{5.6}$$

Note that the minimum feasible value of θ can be computed with equation C.1 in Appendix C.1.1.

Mobile Access Hub Operations and Transit Time

In the case where couriers serving unit zones $z \in Z(a)$ operate from a mobile access hub a that is visited by riders R_a times, operations are composed of two tiers: parcel movement between the local hub and the mobile access hub, and courier routes serving a unit zone from the mobile access hub location. Parcel movement between a local hub and a mobile access hub is characterized by a number of times R_a that the mobile access hub is replenished (i.e. visited by a out-and-back rider trip from the local hub). The operations travel, time and cost can thus be approximated by respectively $2d_{la}R_a + \sum_{z\in Z(a)} D_z(n_z, a)$, $(t^{rider}_{fixed} + \frac{2d_{la}}{s_0^{rider}})R_a + \sum_{z\in Z(a)} T_z(n_z, a)$ and $(c^{rider}_{fixed} + 2d_{la}c_0^{rider})R_a + (t^{rider}_{fixed} + \frac{2d_{la}}{s_0^{rider}})R_a c^{rider}_{wage} + \sum_{z\in Z(a)} C_z(n_z, a)$; where t^{rider}_{fixed} represent the fixed time of a rider route at the local hub and at an access hub, s_0^{rider} represents the speed of a rider vehicle, and c^{rider}_{fixed}, c_0^{rider} and c^{rider}_{wage} respectively represent fixed cost per tour, variable cost per distance traveled and hourly wage of a rider. Moreover, the maximum transit time between local hub l and a customer location in zone z is the maximum between the maximum transit time for inbound operations, say $T^{transitIB}_{az}$, and the maximum transit time for outbound operations, say $T^{transitOB}_{az}$. The maximum transit time for inbound operations is the time a courier takes to move from the first stop on their route to the mobile access hub, plus the maximum time parcels may wait in the mobile access hub (time between two rider visits), plus the time a rider takes to travel from the mobile access hub to the local hub l and can be approximated as follows:

$$T^{transitIB}_{az} = Q^a_z\left(\frac{k(\delta_z)^{-\frac{1}{2}}}{s^{courier}} + t^{courier}_{stop}\right) + Q^a_z v t^{courier}_{handling} + \frac{1}{2}t^{courier}_{fixed} + \frac{d_{az}}{s_0^{courier}}$$

$$+\frac{\Delta}{R_a+1}+t^{rider}_{fixed}+\frac{d_{la}}{s^{rider}_0}$$

Where Q^a_z is the number of stops on a single courier route leaving from mobile access hub location a, Δ is the total time of operations, and $\frac{\Delta}{R_a+1}$ is the inter-arrival time of riders at the mobile access hub.

The maximum transit time for outbound operations is the time a rider takes to travel from the local hub to the mobile access hub, plus at most the time for a courier to finish a complete route, plus the time it takes for a courier to travel from the mobile access hub to the last customer stop on their route, and can be expressed as follows:

$$T^{transitOB}_{az}=t^{rider}_{fixed}+\frac{d_{la}}{s^{rider}_0}+3\frac{d_{az}}{s^{courier}_0}+\frac{3}{2}t^{courier}_{fixed}+2Q^a_z\left(\frac{k(\delta_z)^{-\frac{1}{2}}}{s^{courier}}+t^{courier}_{stop}\right)+2Q^a_z v t^{courier}_{handling}$$

The difference between the maximum transit time for inbound operations and the maximum transit time for outbound operations is:

$$T^{transitIB}_{az}-T^{transitOB}_{az}=\frac{\Delta}{R_a+1}-\left(t^{courier}_{fixed}+\frac{d_{az}}{s^{courier}_0}+Q^a_z\left(\frac{k(\delta_z)^{-\frac{1}{2}}}{s^{courier}}+t^{courier}_{stop}\right)+Q^a_z v t^{courier}_{handling}\right)$$

Which is the difference between the inter-arrival time of riders visiting the mobile access hub and the length of one courier route operating from the mobile access hub. The assumption is made that multiple courier routes can be performed between two rider visits, which implies $T^{transitIB}_{az}\geq T^{transitOB}_{az}$. To satisfy the maximum transit time requirement, Q^a_z and R_a can be adjusted as long as Q^a_z is inferior or equal to a courier's carrying capacity expressed in number of stops. It is decided to prioritize courier productivity (number of stops on a route Q_z^a) over replenishment frequency R_a as long as $R_a \leq \bar{R}$. Algorithm 2 in Appendix C.1 sets Q_z^a and R_a to satisfy the transit time constraint when feasible for z unit zones served by mobile access hub a, and to the shortest possible transit time otherwise. It prioritizes courier efficiency by iteratively decreasing the length of courier routes and computing the required rider visit frequency to meet the transit time constraint. Note that the minimum feasible value of θ can be computed with equation C.2 in Appendix C.1.1.

5.3.4 Mobile Access Hub Deployment Optimization

Coming back to the optimization challenge (5.1), an integer program can be formulated using the cost estimates proposed in section 5.3.3 where binary decision variables X_a indicate the deployment of a mobile access hub in candidate location a (i.e. serving unit zones $z \in Z(a)$).

The associated deployment cost can be expressed as the depreciation cost for each of the mobile access hubs in the fleet, plus the transportation cost of a mobile access hub from the local hub to location a and the cost of reserving space in location a for the duration of operations for each deployed mobile access hub. This deployment cost for candidate location a can be expressed as $c_a = 2d_{la}c^{mah} + h_a$ where d_{la} is the distance between the local hub and location a, c^{mah} is the variable transportation cost per distance traveled for a mobile access hub, and h_a is the price paid for reserving location a for the duration of operations; That is, $C^D(x) = Mc^d + \sum_{a \in A} c_a X_a$ where c^d is the depreciation of a mobile access hub during one operations period.

The operations costs of riders moving parcels between the local hub and access hubs ca be expressed as $C^R(x, \sum_{z \in Z} n_z) = ((c^{rider}_{fixed} + 2d_{la}c^{rider}_0)R_a + (t^{rider}_{fixed} + \frac{2d_{la}}{s^{rider}_0})R_a c^{rider}_{wage})X_a$ which is accounted for only if a mobile access hub is deployed in location a (i.e. $X_a = 1$).

Operations costs of couriers serving unit zones can be expressed as $C^C_z(x, n_z) = C_z(n_z, l)Y_z + \sum_{a: z \in Z(a)} C_z(n_z, a)X_a$ where Y_z is a binary variable equal to 1 if unit zone z is served by a mobile access hub, and 0 otherwise. The relationship between variables Y_z and X_a can be expressed by the set of mathematical constraints $Y_z = 1 - \sum_{a:z\in Z(a)} X_a$ ensuring that a unit zone is served either from a mobile access hub or from the local hub, and $\sum_{a:z\in Z(a)} X_a \leq 1$ ensuring that unit zone z can be served by at most one mobile access hub at the time. Due to the structure of the proposed cost functions and the properties of the expected value of random variables, the expected value of operations costs as expressed in optimization challenge 5.1 is equivalent to operations costs for the average number of stops, say $\bar{n}_z = \mathbb{E}[n_z]$.

Finally, optimization challenge (5.1) can be formulated as the following integer program:

$$\min \sum_{a\in A} \left(c_a + (c^{rider}_{fixed} + 2d_{la}c^{rider}_0)R_a + (t^{rider}_{fixed} + \frac{2d_{la}}{s^{rider}_0})R_a c^{rider}_{wage} \right) X_a$$

$$+ \sum_{z\in Z} C_z(\bar{n}_z, l)Y_z + \sum_{a:z\in Z(a)} C_z(\bar{n}_z, a)X_a + Mc^d \tag{5.7}$$

$$s.t.\ Y_z = 1 - \sum_{a:z\in Z(a)} X_a, \forall z \in Z \tag{5.8}$$

$$\sum_{a:z\in Z(a)} X_a \leq 1, \forall z \in Z \tag{5.9}$$

$$\sum_{a\in A} X_a \leq M \tag{5.10}$$

X_a, Y_z integer

Objective function (5.7) aims at minimizing mobile access hub deployment costs plus the total expected cost of operations as defined by (5.1). Constraints (5.8) are linking constraints forcing the model to account for a unit zone's baseline operations costs if no mobile access hubs is deployed to serve it. Constraints (5.9) ensures that at most one mobile access hub is serving a specific unit zone. Constraint (5.10) limits the number of mobile access hub deployments based on the number of mobile access hub available M.

5.4 Results

In this section, results of a set of numerical experiments are provided to give an understanding of the impact of different design parameters and to assess the potential of mobile access hub deployments in urban parcel logistics. First, operations associated with a single mobile access hub serving a unit zone are examined to observe the impact of a set of design parameters on the economic viability of operations using a mobile access hub. Then, sensitivity analysis results on the deployment of a set of mobile access hubs over a synthetic local cell composed of several unit zones are provided to examine the impact of different factors on the performance of such solution. Finally, sample results from a case inspired by a large parcel express carrier operations are presented to assess the potential of mobile access hub deployments in a real-world context. All experiments were implemented in Python 3.7 using Gurobi 9.0 as the solver and were computed on a laptop with an Intel Core i5-7200U CPU @ 2.50GHz.

5.4.1 Assessing Economic Viability of a Mobile Access Hub

Consider a unit zone z located d_{lz} away from a local hub (distance between the hub and the average location in the unit zone). Suppose a mobile access hub a can be deployed on a line between the local hub and the unit zone so that $d_{lz} = d_{la} + d_{az}$, as illustrated in Figure 5.2. Define a stem distance ratio r such that $d_{az} = rd_{lz}$ and $d_{la} = (1 - r)d_{lz}$.

Let the economic load be the minimum pickup and delivery load in the unit zone that ensures operations using the mobile access hub are cheaper than the baseline (i.e. courier operating from the local hub). The economic load can be computed by solving the follow-

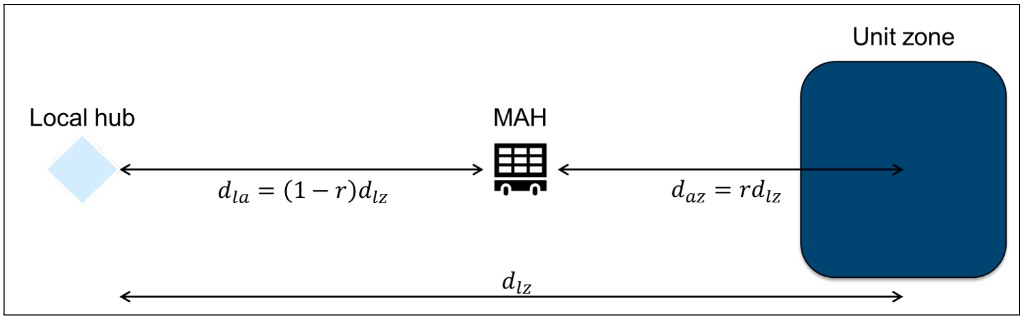

Figure 5.2: Illustration of a Mobile Access Hub Serving a Unit Zone

ing linear equation for n:

$$C_z(n,l) - (c^{rider}_{fixed} + 2d_{la}c^{rider}_0)R_a - (t^{rider}_{fixed} + \frac{2d_{la}}{s^{rider}_0})R_a c^{rider}_{wage} - C_z(n,a) = 0$$

That is, if the pickup and delivery load of the unit zone greater than the economic load, mobile access hub operations are cheaper than the baseline (without accounting for deployment costs). Figure 5.3 provides sensitivity analysis for the economic load against the stem distance ratio r, the distance between the local hub and the unit zone d_{lz}, the average courier stem speed $s^{courier}_0$ and the transit time constraint θ. Default parameter values are listed in Appendix C.2.1.

The first observation from Figure 5.3-a is that as the transit time constraints become tighter (i.e. smaller θ values), economic load values increase. This is due to the fact that the rider visit frequency R_a has to be adjusted to reduce the waiting time in the mobile access hub, and the travel time between the mobile access hub and the local hub.

Secondly, Figure 5.3-b shows that the economic load slowly increases with the stem distance ratio r on the interval $[0, 0.5]$ which suggests that mobile access hubs can be located near but not within the unit zone they serve and still enable operations cost savings. This is even more important when considering mobile access hubs serving several unit zones by being located for instance at their intersection.

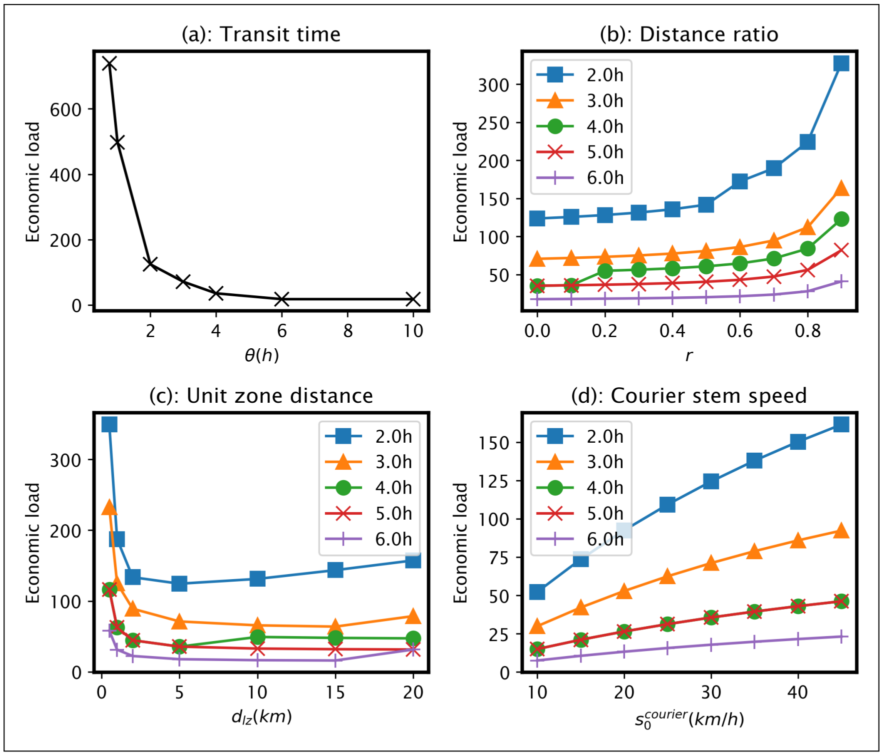

Figure 5.3: Economic Load Assessment for a Mobile Access Hub Serving One Unit Zone for Different Maximum Transit Time Constraints

Thirdly, 5.3-c displays the economic load against the distance between the local hub and the unit zone. When the unit zone is very close to the local hub, a mobile access hub does not seem to make sense as the economic load goes to infinity as the distance d_{lz} tends towards 0. However, the economic load quickly decreases as the unit zone becomes more distant from the local hub.

Lastly, the constraints on courier vehicles operating in dense urban areas often limit courier's carrying capacity and average speed. While performing pickup and deliveries in a unit zone, speed may be limited by the stop density and the road infrastructure often limits couriers to operate lightweight vehicles. Such vehicles may have limited speed when traveling between the local hub and the unit zone ($s_0^{couriers}$), which couriers have do to often due to their limited carrying capacity. Figure 5.3-d shows that the economic load decreases with $s_0^{couriers}$. That is, it suggests that when couriers are limited to slower lightweight vehicles, mobile access hubs become more relevant.

5.4.2 Assessing the Performance of Mobile Access Hub Deployments

In order to assess different factors impacting mobile access hubs deployment performance over several unit zones served by a single local hub while breaking free from the impact of specific geography, a synthetic local cell instance is considered. The instance is composed of rectangular unit zones of dimensions 1km by 1.5km arranged in a 6 by 6 local cell with 20m inter-zone interstices served by a local hub located at the bottom left corner. Each unit zone is operated daily for 10 hours ($\Delta = 10h$), and is subject to normally distributed expected demand in terms of number of stops $\bar{n}_z \sim \mathcal{N}(\mu, \sigma)$. Each experiment presented in this section is performed over 1000 demand instances (i.e. days) generated by Monte Carlo simulation for which, unless stated otherwise, default values are defined as the mean $\mu = 200$ and the coefficient of variation $\frac{\sigma}{\mu} = 0.2$. Candidate mobile access hub locations are defined as the combination of (1) centroids of each unit zone, able to serve the unit zone itself, and (2) the midpoint on the segment between two centroids, able to serve the corresponding two unit zones, for each pair of neighboring unit zones. Figure 5.4 illustrates the synthetic instance and its set of candidate locations.

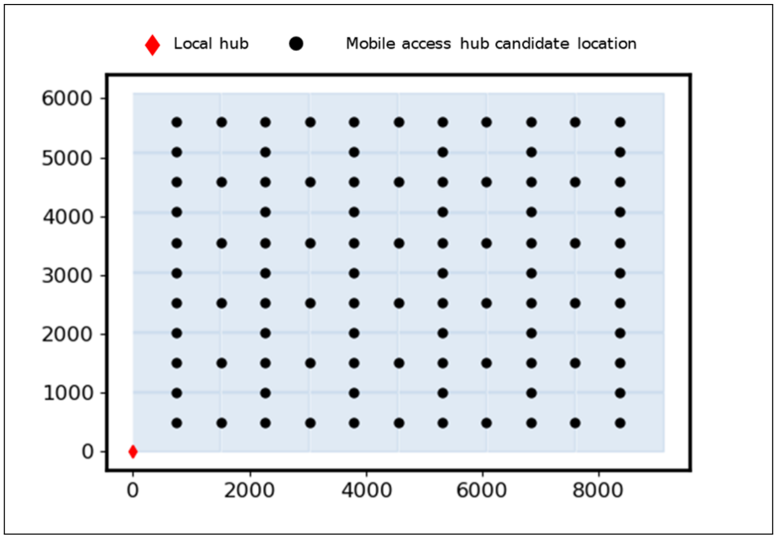

Figure 5.4: Synthetic Local Cell Grid and Mobile Access Hub Candidate Locations

Impact of Demand Variability

Demand variability σ impacts the diversity of demand realizations from one day to another. In terms of mobile access hub deployments, a low variability context makes deployments more likely to be similar day after day than a context where demand is highly volatile. Figure 5.5 illustrates this by displaying the frequency of mobile access hub deployments at each location used for different coefficients of variation $\frac{\sigma}{\mu}$ by changing the value of σ. Figure 5.5-a (low variability) shows that a few locations at the perimeter of the local cell are more frequently used for mobile access hub deployments, which indicates that these locations are used in most of the 1000 deployments in the sample. Moreover, a few locations close to the local hub are rarely used, and all locations that are used are serving two unit zones. Comparatively, Figure 5.5-b (high variability) shows a more homogeneous deployment frequency over the set of used locations, with a medium deployment frequency over all candidate locations serving two unit zones, and a low deployment frequency over all candidate locations serving a single unit zone.

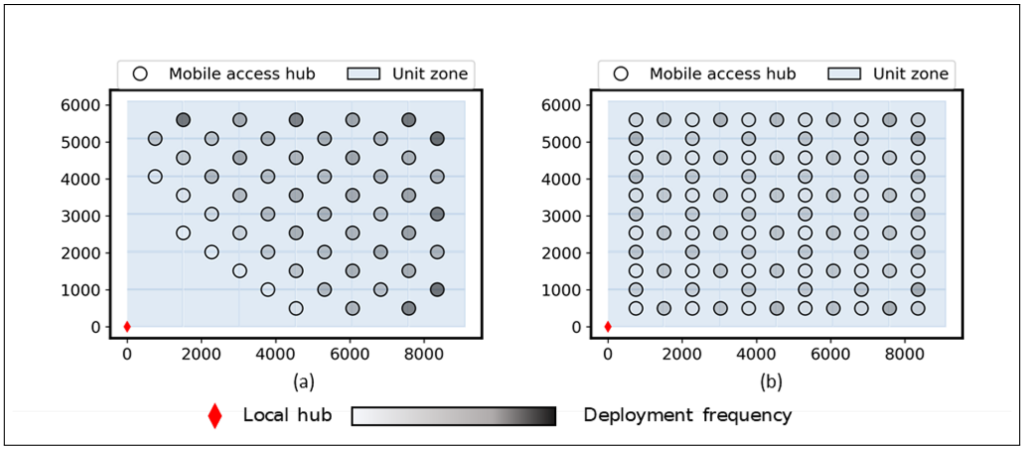

Figure 5.5: Mobile Access Hub Deployments with (a) $\frac{\sigma}{\mu} = 20\%$ and (b) $\frac{\sigma}{\mu} = 200\%$

Figure 5.6 presents cost saving distributions for different coefficients of variation (i.e. for different values of σ). The spread of cost saving distributions increase with demand variability, which confirms the diversity of demand realizations from one day to another for high coefficients of variation. Moreover, Figure 5.6 shows that for the same demand mean value μ, cost savings increase with demand variability. That is, local cells where demand is highly variable seem to better benefit from mobile access hub deployments.

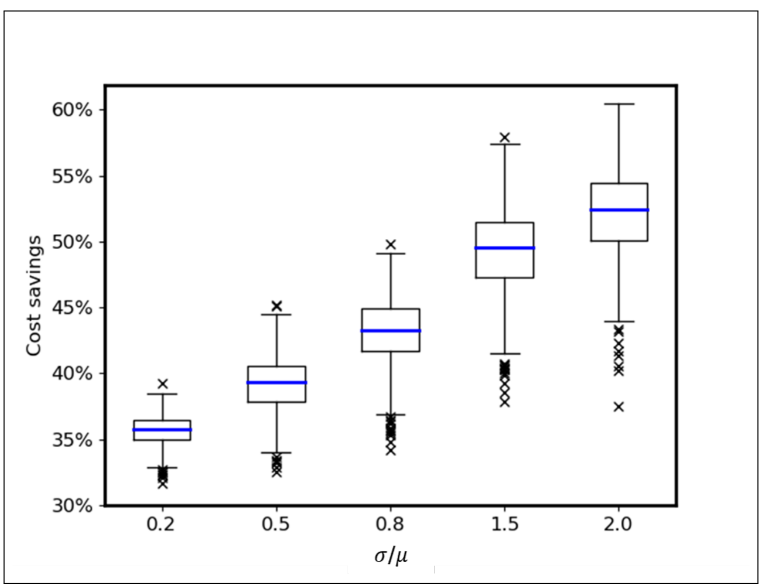

Figure 5.6: Savings as a Function of Coefficient of Variation $\frac{\sigma}{\mu}$

Impact of Transit Time Constraints

The maximum transit time as defined in section 5.3.1 impacts the profitability of each mobile access hub candidate location by determining the number of rider trips between the local hub and the mobile access hub. Additionally, the maximum transit time may also limit the maximum number of stops on a courier route, and therefore impact both the baseline operations costs and the cost of operations of mobile access hub candidates. Figure 5.7 displays performance indicators defined in section 5.3.2 for maximum transit time values ranging from 1h to 8h.

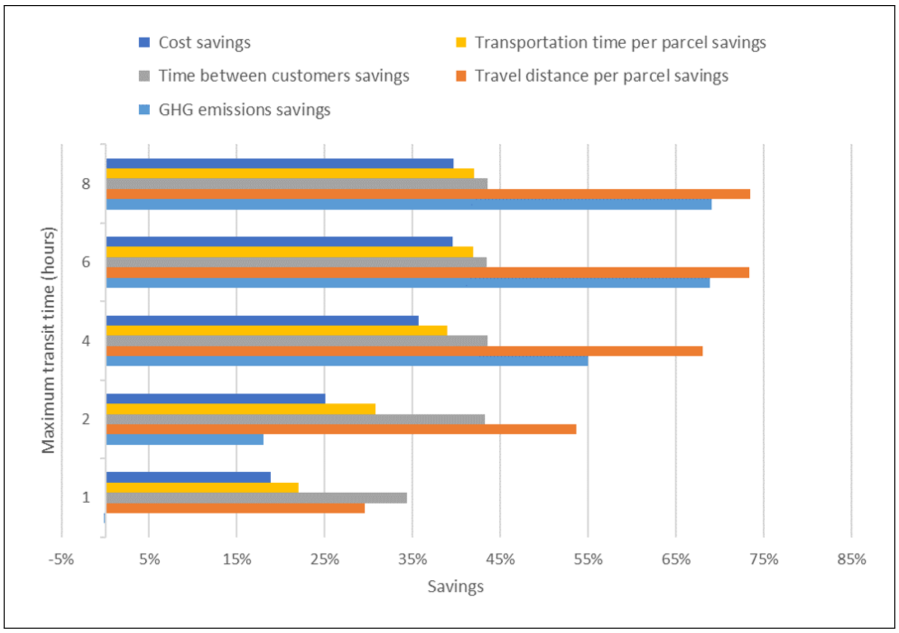

Figure 5.7: Savings as a Function of Maximum Transit Time θ

Every performance indicator increase with the maximum transit time value; the advantages of using mobile access hubs are greater when the time constraint is not too tight as less overall vehicle movement is required for each mobile access hub candidate (i.e. rider trips). However, savings are still significant for tight time constraints. For instance, for $\theta = 1$h, mobile access hubs provide significant cost, time and travel savings compared to baseline operations even if greenhouse gas emissions are not improved in this case as

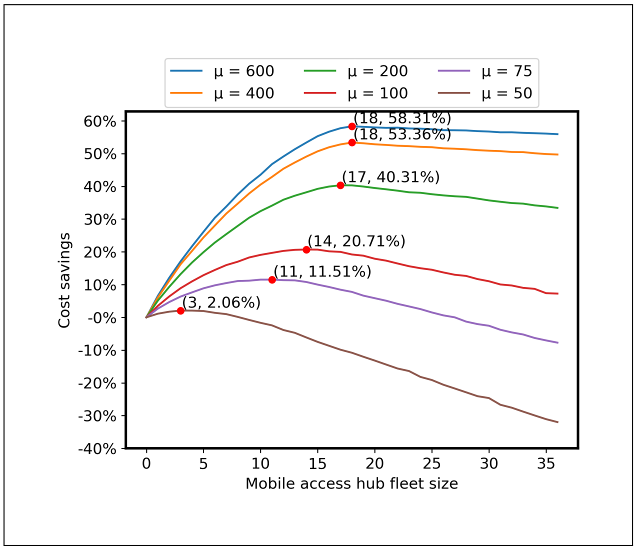

Figure 5.8: Savings as a Function of Fleet Size for Different Demand Levels

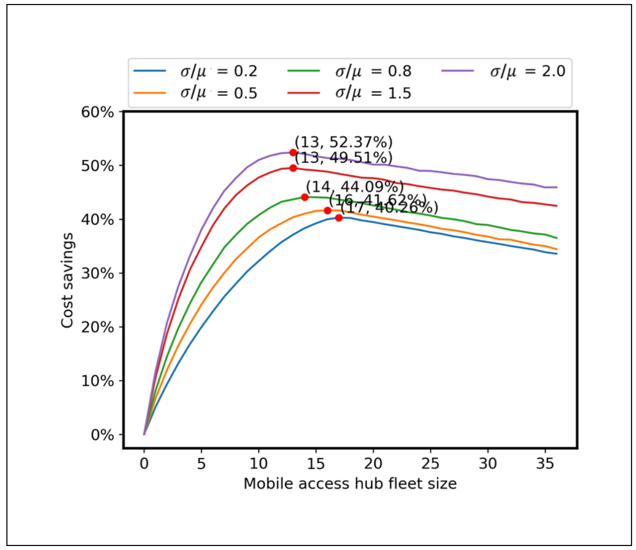

Figure 5.9: Savings as a Function of Fleet Size for Different Demand Variability

a result of the high frequency of rider vehicle movements and their relative greenhouse gas emissions efficiency.

Impact of Mobile Access Hub Fleet Size

The number of mobile access hub available to deploy, or the mobile access hub fleet size M, directly impacts the cost efficiency of solutions as mobile access hubs depreciate whether or not they are deployed. That is, having a large fleet may results in reduced or even negative cost savings, and lower fleet utilization. Similarly, having a small fleet may reduce the potential cost savings by missing opportunities to deploy mobile access hubs in profitable locations, but has the advantage of avoiding negative savings and ensuring high fleet utilization. Figures 5.8 and 5.9 show the evolution of cost savings as a function of fleet size for different demand levels μ and different demand coefficients of variation.

Both Figures 5.8 and 5.9 show that cost savings increase with the fleet size until a maximum is reached (i.e. the optimal fleet size, marked as a red dot), before decreasing asymptotically linearly (accordingly to the depreciation rate). Additionally, Figure 5.8 shows that the optimal fleet size increases as μ increases, which indicates that more mobile access hub locations become profitable. And, Figure 5.9 shows that the optimal fleet size decreases as demand variability increases, as mobile access hub candidate locations are less frequently profitable.

5.4.3 Illustrative Case

This section provides sample results for a case inspired from urban operations of a large parcel express company to assess the potential of mobile access hub deployments in the real-world context. The case is inspired from a relatively dense part of an Asian megacity. Figure 5.10 illustrates the examined local cell's geography and demand density along with a set of mobile access hub candidates located at the center or close to the border and the intersection of unit zones and each serving up to two neighboring unit zones. The local cell is composed of 73 unit zones covering 12 square kilometers, with heterogeneous demand $\bar{n}_z \sim \mathcal{N}(\mu_z, \sigma_z)$. The case is geographically more compact than the synthetic grid illustrated in Figure 5.4, but features more diverse unit zone dimensions and demand densities. Demand averages μ_z range from 0.35 to 943.8 stop per day (each unit zone is operated daily for 10 hours) with coefficients of variation ($\frac{\sigma}{\mu}$) ranging from 19.7% to 140.6% (see demand histograms in Figure C.1 in Appendix C.2.2).

Figure 5.11 displays average values of key performance indicators for 1000 Monte Carlo simulation scenarios on the illustrative case for different values of the maximum transit time θ and for optimal fleet sizes. Complete results and sample deployments are presented respectively in Table C.2 and Figure C.2 in Appendix C.2.2. The range of values for θ is chosen to have realistic cases based on the fact that baseline operations without transit time constraint have a maximum transit time of 1h. Figure C.3 in Appendix C.2.2 displays the identification of optimal fleet sizes.

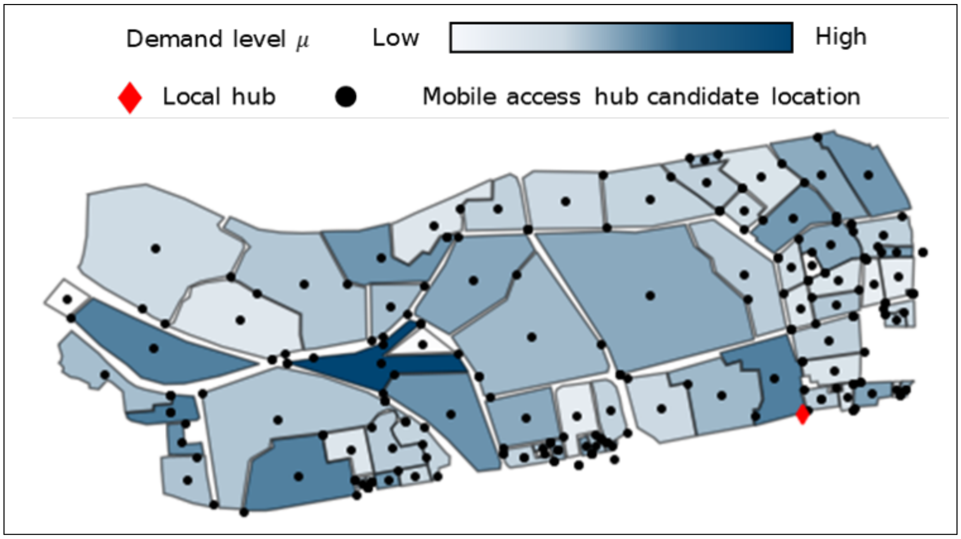

Figure 5.10: Illustrative Case

Figure 5.11 shows that for a tight maximum transit time of 1h, mobile access hub deployments can save up to 10.55% of operations cost on average bringing the total cost per parcel from $0.41 to $0.37, saving on average $865/day or about $315,000 a year operating every day. Total transportation time savings are evaluated to 12.81% on average, with time between customer savings of 20.28% indicating a significant gain in courier productivity (more time spent performing pickup and deliveries versus traveling from a hub to a unit zone). While travel distance savings are evaluated to 37.86% on average which may significantly reduce negative externalities, greenhouse gas emissions are only reduced by 10.31% as the maximum transit time constraint forces riders to travel between the local hub and mobile access hubs very frequently.

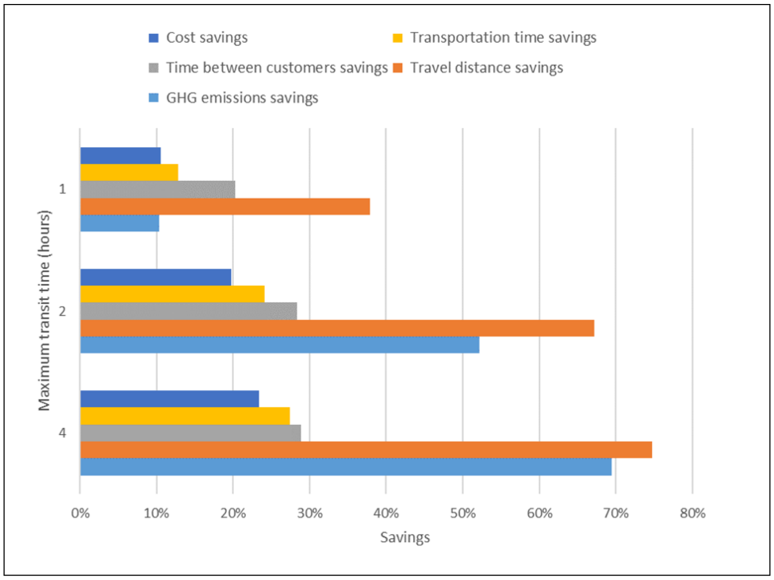

Figure 5.11: Illustrative Case Savings for Different Maximum Transit Times

Relaxing the maximum transit time constraint to 2h almost doubles average cost savings bringing the total cost per parcel down to 0.30$, saving on average $1,724/day or about $630,000 a year operating every day. It also significantly increases time and travel savings, and multiply greenhouse gas emissions savings by a factor of 5 (up to 52.15% on average). The relaxation of the maximum transit time constraint to 2h may be reasonable to consider operationally, motivated by significant additional savings and the gain on environmental efficiency and negative externalities reduction. Such considerations highlight a trade-off between operational efficiency mostly driven by cost and time efficiency and sustainability related to environmental aspects.

Figure 5.11 also shows that further relaxing the maximum transit time constraint to 4h has a lighter impact on savings over the different key performance indicators. Considering that speed is one of the important components of urban parcel logistics, further increasing the maximum transit time constraint is not likely to be an option that makes sense operationally, especially as it is not supported by significant additional savings.

5.5 Conclusion

This chapter contributes to the development of sustainable vehicle-based alternatives in urban parcel logistics by expanding the understanding of characteristics influencing the performance of mobile access hub deployments and assessing the potential of using such a solution in last-mile distribution with an illustrative case inspired from a large parcel express carrier operations. In particular, it proposed a mathematical modeling framework to assess the economic, time efficiency and environmental performance of mobile access hub deployments through synthetic and illustrative cases.

The analysis revealed that under very tight maximum transit time requirements, mobile access hubs can only be profitable if they are handling large loads; however, the economic load decreases quickly as maximum transit time requirements increase. Furthermore, the profitability threshold of a mobile access hub is flexible relatively to its distance from the demand zone; that is, mobile access hubs do not need to be placed in the center of the zone where pickups and deliveries are performed to be profitable and can be located in anywhere within or very close to the zone. The analysis also revealed that the value of mobile access hubs is greater when demand is highly variable, and result in more diverse deployments than in the case of low variability where mobile access hubs are deployed in the same location more frequently. While the number of mobile access hubs available to deploy impacts overall profitability, each increment in fleet size brings significant additional savings, until the optimal fleet size is reached and overall performance starts decreasing due to unused mobile access hubs.

The illustrative case, inspired from operations of a large parcel express carrier, suggests respectively up to 10.55% and 19.78% cost savings under very tight and tight maximum transit time constraints for optimal fleet sizes. It also suggests potential in reducing negative externalities and environmental impact with up to respectively 37.86% and 67.19%

travel distance savings and 10.31% and 52.15% greenhouse gas emission savings under very tight and tight maximum transit time constraints. The illustrative case emphasizes a trade-off between operational efficiency and environmental sustainability that can be balanced to achieve global sustainability goals while being economically sound. For instance, environmental sustainability can be greatly improved by reasonably relaxing very tight transit time constraints.

This chapter suggests that mobile access hub deployments for urban parcel delivery has significant potential both economically and environmentally, with the manageable downsides of having to deal with a dynamic fleet of hubs and the addition of extra-handling due to transshipments. While for instance implementation may require a more agile workforce, potential productivity gain can motivate couriers to accept changes in their daily tasks.

Finally, there are numerous research avenues to further develop sustainable systems using mobile access hubs. For instance, studying flow dynamics through simulation studies can help better understand the utilization of hubs relative to their capacity, potentially further optimizing the dynamic use of urban space. Dynamic routing strategies can then be developed to better replenish hubs, further increasing the overall economic and environmental potential. Mobile access hubs can also relocated throughout the day or be considered as an option to complement fixed access hub networks by temporarily enhancing network capacity in the context of dynamic pooled capacity deployments as suggested in [150].

CHAPTER 6

CONCLUSION AND FURTHER RESEARCH

6.1 Summary of Contributions and Results

In this dissertation we presented a set of methods to design and manage capillary logistics networks and identify key managerial insights to shape urban parcel logistics. Leveraging concepts of the Physical Internet, we examined the impact of modularity, hyperconnectivity and mobility on the design and management of innovative smart locker bank and access hub networks. Experimental results have shown that the studied innovations may yield significant savings fostering both the economic and the environmental sustainability of urban parcel logistics operations. The remainder of this section summarizes the primary results of the presented work.

The four design options proposed for smart locker banks range from currently implemented monolithic designs to most modular designs using PI-containers. While monolithic designs are easier to implement and can be optimally configured at the location level, they are typically unable to adapt to evolving demand. Modular designs may adjust local and global capacity and gradually change configurations, but require the management of spare modules, configurations based on standard patterns, and rely on more complex technology.

This research proposed optimization based methodologies for designing monolithic and modular smart locker banks and demonstrated that modular designs can perform just as well as modular designs while being more flexible under evolving demand by being reconfigurable.

Then, this research examined access hub networks and studied the dynamic deployment of pooled storage capacity in access hub networks operating under space-time uncertainty. We proposed a two-stage stochastic program formulation of the decision problem with synchronization of underlying operations through travel time estimates. We then proposed a solution approach based on a rolling horizon algorithm with lookahead and a benders decomposition able to solve large scale instances of a real-sized megacity. Results show that the proposed approach produces solutions in a reasonable time even for large scale instances of up to 838 hubs. They suggest that a dynamic capacity deployment strategy with capacity pooling has a significant advantage over a static capacity deployment strategy for access hub networks.

Finally, this research examined the use of mobile access hub deployments to make dynamic use of urban space for logistics needs. We expanded the understanding of characteristics influencing the economic and environmental efficiency of mobile access hub deployments by proposing a modeling framework and an integer program to assess performance of mobile access hub deployments, and studying the impact of a set of design parameters. Results showed design flexibility relative to the location of hubs and pronounced advantages in highly variable environments. Results also highlighted the value of mobility by showing significant savings potential in terms of cost and time efficiency as well as environmental sustainability and emphasizing a trade-off between operational efficiency and environmental sustainability that can be balanced to achieve global sustainability goals while being economically sound.

6.2 Recommendations for Research Avenues

Throughout the work presented in the previous chapters, we identified a set of research avenues. Here, we aim at giving directions for further research as direct extensions or in line with the contributions and the results presented in this dissertation:

Smart Locker Banks

- Development of methods to design PI-container based smart locker banks and analysis comparing their global performance to other design options.
- Development of predictive analytics for forecasting future needs and preemptively adjust smart locker bank network capacity and configuration.
- Development of methods to optimize sets of modular towers to be used across smart locker bank networks.
- Analysis of the relative performance of an overall network of smart locker banks under various design options, capacity and configurations, and operations policies through simulation experiments.

Access Hubs

- Development of methods to manage networks featuring both fixed, modular, and mobile access hub capacity with various relocation frequencies for each solution.
- Analysis of operations policies such as dynamic routing and staffing to unlock the potential of capacity pooling not only as a recourse but as an integral part of network design and operations planning.
- Development of dynamic routing strategies to better replenish hubs, further increasing the overall economic and environmental savings potentials
- Analysis of flow dynamics through simulation studies to better understand the utilization of hubs relative to their capacity.

Appendices

APPENDIX A
CHAPTER 3

A.1 Simple Parameters

Parameter	Description	Value (location)
α^G	Minimum average service level	90%
α^L	Minimum service level for each individual scenario	75%
c^M	Cost of an interactive module	50
c^S	Unitary bank surface cost	50
c^W	Unitary bank width cost	500
$\bar{h}$	Upper bound on the height of the bank	15
λ	Amortization factor for acquisition and implementation costs over the considered period	$1/2*5*12$
$\underline{m}$	Minimum distance required between two consecutive interactive modules	7
n^M	Number of locker columns an interactive module can cover	14
$\bar{w}$	Upper bound on the width of the bank	20(1) , 20(2) , 25(3) , 30(4)
w	Width of the considered modular tower in terms of grid units	2

A.2 Revenues

r_{ds} Unit revenue yield by serving an order for dimension d in scenario s

Package Dimensions	1 (1x1)	2 (1x2)	3 (1x3)
Revenue associated*	6.10	11.95	16.35

* Considered independent of the scenario for the experiment.

A.3 Ergonomic Costs

$$c^A_{11l} = \begin{cases} 0.01 * (115 - 15y(l)) & \text{if } y(l) \leq 7 \\ 0.01(-95 + 15y(l) & \text{if } y(l) > 7 \end{cases}$$

$$c^A_{12l} = \begin{cases} 0.01 * ((75 + (65/6)) - (65/6)y(l)) & \text{if } y(l) \leq 7 \\ 0.01(10 - 7(65/6)) + (65/6)y(l) & \text{if } y(l) > 7 \end{cases}$$

$$c^A_{13l} = \begin{cases} 0.01 * ((50 + (40/6)) - (40/6)y(l)) & \text{if } y(l) \leq 7 \\ 0.01(10 - 7(40/6)) + (40/6)y(l) & \text{if } y(l) > 7 \end{cases}$$

$$c^A_{22l} = 0.01 * ((10 - (65/14)) + (65/14)y(l))$$

$$c^A_{23l} = 0.01 * ((10 - (90/14)) + (90/14)y(l))$$

$$c^A_{33l} = 0.01 * ((10 - (90/14)) + (90/14)y(l))$$

Where $y(l)$ is the height of location l, in grid units.

A.4 Modular Towers

Type	1	2	3	4	5	6	7	8
Cost*	1941.8	1941.8	1911	1911	1911	1911	1911	1911
m^i	1	1	0	0	0	0	0	0

* As 70% of the equivalent fixed-configuration locker bank design cost.

$\delta^{m}_{ii'} = 7$.

APPENDIX B

CHAPTER 4

B.1 In-sample Variability

In-sample variability was tested with no lookahead for instance A with capacity pooling limited to 1 km for 10 samples. Results are presented in Table B.1. Coefficient of variation represent the ratio between the standard deviation and the average of solutions' total cost. Statistical gap represent the ratio $(UB - LB)/LB$ where UB and LB are respectively the highest and lowest total cost in the sample.

Table B.1: In-sample statistical analysis

Number of scenarios	5	10	20	30	50	75	100	200
Coefficient of variation	3.47%	2.87%	2.70%	2.11%	1.34%	1.04%	0.52%	0.41%
Statistical gap	10.04%	9.16%	8.57%	7.85%	4.25%	3.51%	1.53%	1.22%

B.2 Cost Estimates

The capacity module relocation costs r_a include an operational cost of \$1.50 per kilometer, and a fixed cost of two operators for two hours at a rate of \$10 per hour to uninstall/install modules once at the desired locations:

$$r_a = 1.50 d_a + 40, \forall a = (i, j) \in A$$

Where d_a is the distance between location i and j such that $a = (i, j)$.

The holding costs are computed from an amortized acquisition cost of \$2000 over 5 years (52 weeks long years), and from a rent cost of \$75 per square meter times a location specific factor $(1 + f_l)$ randomly generated to represent the real estate difference between locations.

$$h_l = \frac{2000}{5 * 52} + 75(1 + f_l), \forall l \in L$$

Where f_l is randomly generated from a uniform distribution over [2%, 15%]. It is also assumed that modules do not depreciate when stored at depots ($h_l = 0, \forall l \in D$).

B.3 Other Input Parameters

Parameter	Value	Parameter	Value
c_v^C	\$1/km	s_0^R	50 km/h
c_{v0}^C	\$0.8/km	$\hat{S}_l$	15 $modules$
c_f^R	\$10	t_a^C	1 min
c_v^R	\$1.8/km	t_u^C	2 min
c_{v0}^R	\$1.2/km	t_a^R	5 min
k^C	1.15	t_u^R	1 min
k^R	0.82	t_s^R	5 min
p_l	100000/$module$	v	0.75 m^2
s^C	7 km/h	v^C	0.48 m^2
s_0^C	15 km/h	v^R	6.40 m^2
s^R	30 km/h		

APPENDIX C

CHAPTER 5

C.1 Mobile Access Hub Modeling

C.1.1 Transit Time Feasibility

The minimum value for the transit time constraint θ in the case of baseline operations, say $theta_{min}^{baseline}$ is equivalent to the maximum transit time with courier performing out-and-back trips between the local hub and customers (i.e. $Q_z^l = 1$) and is expressed as follows:

$$\theta_{min}^{baseline} = \frac{1}{2} t_{fixed}^{courier} + \frac{d_{lz}}{s_0^{courier}} + \left(\frac{k(\delta_z)^{-\frac{1}{2}}}{s^{courier}} + t_{stop}^{courier} \right) + v t_{handling}^{courier} \tag{C.1}$$

In the case of mobile access hub operations, θ_{min} the minimum value for θ is equivalent to the largest maximum transit time with maximum replenishment frequency (i.e. $R_a = \bar{R}$) and couriers performing out-and-back trips from the mobile access hub to their respective unit zone(s) (i.e. $Q_z^a = 1$), and is expressed as follows:

$$\theta_{min} = \frac{\Delta}{\bar{R}+1} + t_{fixed}^{rider} + \frac{d_{la}}{s_0^{rider}} + \max_{z \in Z(a)} \left\{ \frac{k(\delta_z)^{-\frac{1}{2}}}{s^{courier}} + t_{stop}^{courier} + v t_{handling}^{courier} + \frac{1}{2} t_{fixed}^{courier} + \frac{d_{az}}{s_0^{courier}} \right\} \tag{C.2}$$

C.1.2 Transit Time Constraint

The following algorithm sets the route lengths Q_z^a and the rider visit frequency R_a to satisfy the transit time constraint when feasible for z unit zones served by mobile access hub a, and to the shortest possible transit time otherwise. It prioritizes courier efficiency by iteratively decreasing the length of courier routes and computing the required rider visit frequency to meet the transit time constraint.

Algorithm 2: Setting Replenishment Frequency and Route Length for a Mobile Access Hub Serving Multiple Unit Zones

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Result: Q_z^a, R_a

for *each unit zone* $z \in Z(a)$ **do**

  $Q_z^a \longleftarrow Q$;

  $R_z \longleftarrow \left\lceil \frac{\Delta}{\theta - t_{fixed}^{rider} - \frac{d_{la}}{s_0^{rider}} - \frac{d_{az}}{s_0^{courier}} - \frac{1}{2} t_{fixed}^{courier} - Q_z^a \left(\frac{k(\delta_z)^{-\frac{1}{2}}}{s^{courier}} + t_{stop}^{courier} \right) - Q_z^a v t_{handling}^{courier}} - 1 \right\rceil$;

  while $R_z > \bar{R}$ *or* $R_z < 0$ **do**

    $Q_z^a \longleftarrow Q_z^a - 1$;

    $R_z \longleftarrow \left\lceil \frac{\Delta}{\theta - t_{fixed}^{rider} - \frac{d_{la}}{s_0^{rider}} - \frac{d_{az}}{s_0^{courier}} - \frac{1}{2} t_{fixed}^{courier} - Q_z^a \left(\frac{k(\delta_z)^{-\frac{1}{2}}}{s^{courier}} + t_{stop}^{courier} \right) - Q_z^a v t_{handling}^{courier}} - 1 \right\rceil$;

    if $Q_z^a = 1$ **then**

      break

    end

  end

  if $R_z < 0$ **then**

    $R_z \longleftarrow \bar{R}$

  end

end

$R_a \longleftarrow \max R_z$;

for *each unit zone* z **do**

  $Q_z^a \longleftarrow \left\lfloor \frac{\theta - t_{fixed}^{rider} - \frac{d_{la}}{s_0^{rider}} - \frac{\Delta}{R_a + 1} - \frac{d_{az}}{s_0^{courier}} - \frac{1}{2} t_{fixed}^{courier}}{\frac{k(\delta_z)^{-\frac{1}{2}}}{s^{courier}} + t_{stop}^{courier} + v t_{handling}^{courier}} \right\rfloor$

end

C.2 Mobile Access Hub Deployment Experiments

C.2.1 Default Parameters

Table C.1 displays the default values for parameters used in the set of experiments in section 5.4.

Table C.1: Default Experiment Parameters

Parameter	Value	Description	Parameter	Value	Description
$c^{courier}$	\$0.1/km	*Courier variable cost in tour*	$\bar{Q}$	15 stops	*Courier capacity*
$c_0^{courier}$	\$0.15/km	*Courier variable cost in stem*	$\bar{R}$	33	*Maximum replenishments per day*
$c_{wage}^{courier}$	\$10/h	*Courier hourly rate*	$s^{courier}$	7 km/h	*Courier tour speed*
c^{mah}	\$0.25/km	*Mobile access hub variable transportation cost*	$s_0^{courier}$	30 km/h	*Courier stem speed*
c_0^{rider}	\$0.20/km	*Rider variable cost*	s_0^{rider}	35 km/h	*Rider speed*
c_{wage}^{rider}	\$10/h	*Rider hourly rate*	σ	40	*Standard deviation of load per day*
c_d	\$22/day	*Mobile access hub depreciation*	$t_{handling}^{courier}$	0.5 min	*Courier handling time per parcel*
$GHG^{courier}$	$0.11g/km$[32]	*Courier greenhouse gas emissions*	$t_{setup}^{courier}$	1 min	*Courier setup time*
GHG^{rider}	$0.29g/km$[151]	*Rider greenhouse gas emission*	$t_{stop}^{courier}$	0.5 min	*Courier stopping time*
h_a	\$25/day	*Location reservation cost*	t_{setup}^{rider}	5 min	*Rider setup time per trip*
k	1.15[152]	*Route length estimation constant*	t_{stop}^{rider}	2 min	*Rider stopping time*
μ	200	*Average load per day*			

C.2.2 Illustrative Case

Figure C.1 depicts the demand characteristics (mean demand and coefficient of variation) of unit zones composing the local cell in the illustrative case.

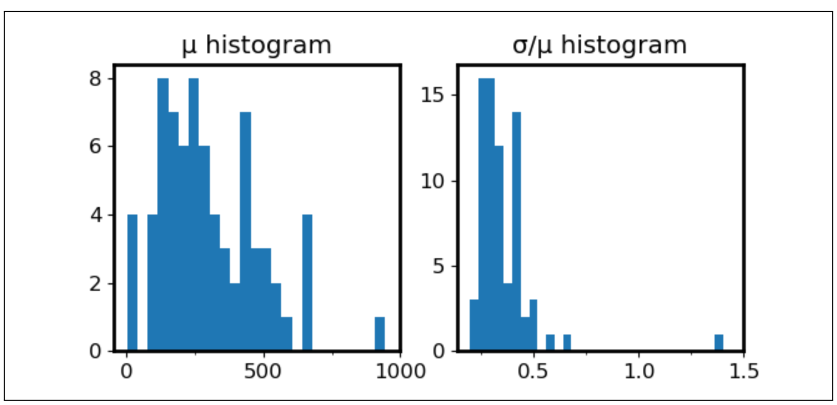

Figure C.1: Demand Histograms for the Illustrative Case

Table C.2: Illustrative Case Results

Max transit time	4:00	2:00	1:00
Fleet size	19	18	9
UZ covered by a MAH	38	36	18
Mean max transit	2:36	1:19	0:37
Max transit	3:53	1:54	0:56
Total cost	$6,283.28	$6,571.65	$7,327.93
Cost per parcel	$0.28	$0.30	$0.37
Cost savings	23.41%	19.78%	10.55%
Transportation time per parcel	1.4 min	1.46 min	1.68 min
Transportation time savings	27.42%	24.08%	12.81%
Time between customers	1.37 min	1.38 min	1.54 min
Time between customers savings	28.90%	28.31%	20.28%
Travel distance per parcel	90 m	120 m	220 m
Travel distance savings	74.77%	67.19%	37.86%
GHG emissions	515.17 kg	537.48 kg	775.82 kg
GHG per parcel	22.96 g	24.54 g	39.17 g
GHG emissions savings	69.49%	52.15%	10.31%

Figure C.2 illustrates samples mobile access hub deployments on the illustrative case instance by displaying the locations of mobile access hubs and their assignments to unit zones when they cover more than one unit zone.

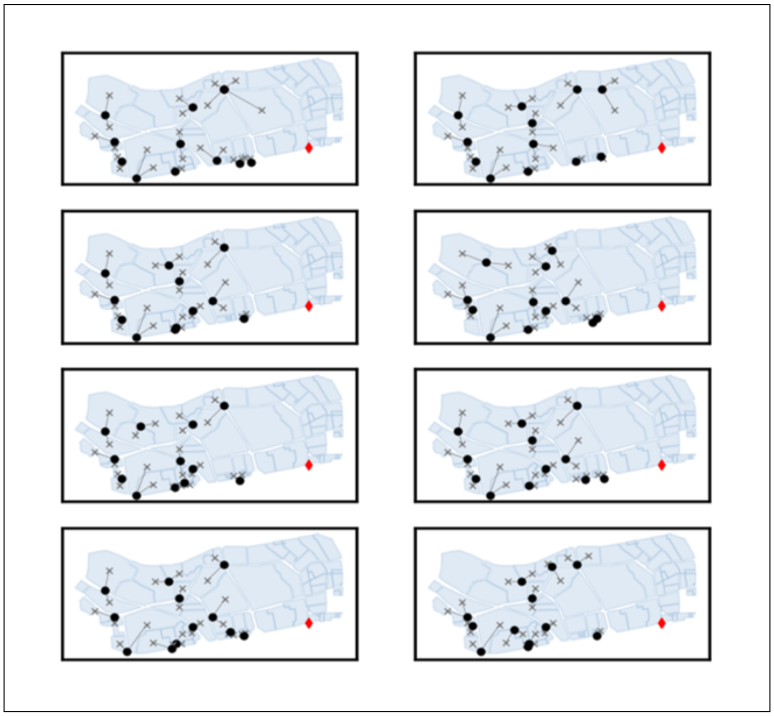

Figure C.2: Sample Mobile Access Hub Deployments for the Illustrative Case

Figure C.3 displays the plot of cost savings against mobile access hub fleet size for difference transit time constraint value for the illustrative case.

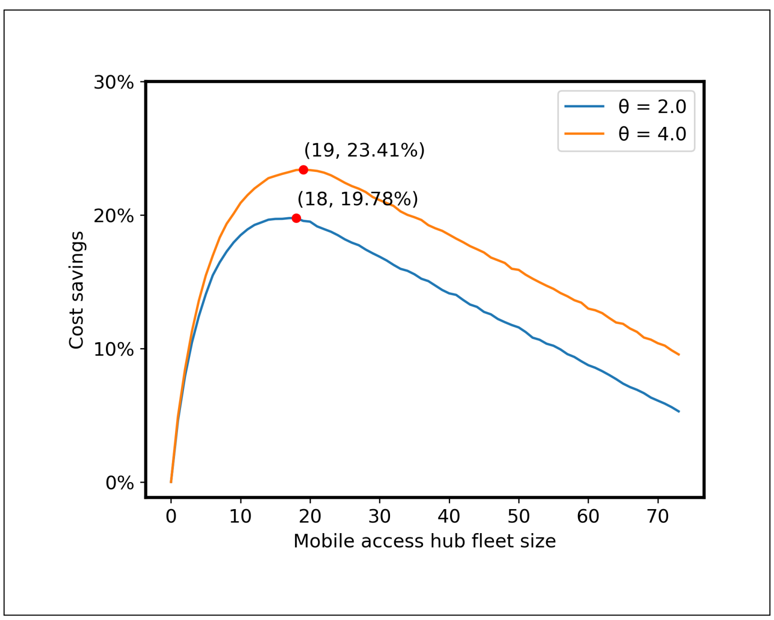

Figure C.3: Fleet Size Analysis for the Illustrative Case

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