Location, capacity, and layout problems of automated parcel lockers

Tal Raviv[a] **and Margaretha Gansterer**[b], [a]Department of Industrial Engineering, Tel Aviv University, Tel Aviv-Yafo, Israel; [b]Department of Operations, Energy and Environmental Management, University of Klagenfurt, Klagenfurt, Austria

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Abstract

The rapid growth of e-commerce has increased the demand for efficient last-mile delivery solutions, with automated parcel lockers (APLs) emerging as a pivotal innovation. This chapter provides a comprehensive overview of the strategic problems related to the location, capacity, and layout of service points in APL networks. It highlights the logistical advantages of APLs, such as reduced delivery costs and enhanced security, while also addressing the complexities involved in their deployment. We review various models and solution approaches tailored explicitly for optimizing APL networks. It also examines the economies of scale, market structure implications, and behavioral aspects influencing the effectiveness of using APLs. By reviewing recent literature and presenting novel models, this chapter offers insights for both academic and practical applications in optimizing APL networks.

Glossary

Automated parcel locker (APL) An automated facility used as a service point for parcel collection by recipients, located in public spaces and providing secure, 24/7 access for parcel collection.
Collection and distribution points (CDPs) Facilities used by retailers to distribute goods to customers. These can be an attended facility or automated and are part of the broader parcel distribution network.
Economies of scale The cost advantage achieved by larger-scale operations, resulting in more efficient resource use. Larger networks and facilities can serve more customers at a lower per-unit cost.
Facility location problem A mathematical problem that focuses on choosing the optimal locations for facilities based on criteria like demand, costs, and accessibility.
Last-mile The final leg of the delivery process involves delivering parcels from a distribution center or service point to the recipient's home.
Pooling effect The benefit of consolidating parcels at fewer, larger service points, leading to higher efficiency and lower rejection rates.
Mobile APLs Automated parcel lockers mounted on vehicles or trailers, offering flexibility in handling overflow demand or serving multiple areas.
Service point (SP) A location where parcels are either dropped off by senders or collected by recipients. SPs can be either attended or automated (like APLs).

Introduction

The rapid growth of the small parcel delivery industry, mainly driven by the explosion of e-commerce in the last two decades, calls for the development of technological innovation and business models. See, for example, GlobeNewswire (2023), Cognitive Market Research (2023), and Mordor Intelligence (2023). The most significant cost component in delivering a parcel from an e-commerce enterprise's central depot to the recipient's home is the last leg (or so-called *last mile*). The last mile is costly because it is not amendable to consolidation and automation of the handling process.

One relatively simple yet important technological advancement in economizing last-mile delivery is the usage of automated parcel locker (APL). An APL is a facility that contains multiple lockers and a terminal. The delivery company can use a network of

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APLs that covers its service area and is accessible to potential recipients. Instead of handing the parcels to the recipients at their addresses, the company drops them in lockers in the APLs selected by the recipients in advance. Once the parcel is stored in a locker, the company notifies its recipient by a text message. The recipients pick up their parcels from the locker at a later time by punching a one-time password (provided in the text message) on a terminal installed at the APL.

We note that some authors refer to APLs as fixed parcel lockers (FPLs) while using the acronym APL to refer to autonomous parcel lockers, that is, automatic parcel lockers that are mounted on autonomous vehicles, see K¨tschau et al. (2023). Also, literature refers to collection and distribution points (CDPs), which are lockers used by retailers to distribute goods to customers (e.g., Xu et al., 2021). However, this paper uses the APL to refer only to stationary automated parcel lockers.

From the delivery company's point of view, using an APL network has clear logistical advantages over delivering the parcel to the recipient's address. The APLs allow a certain degree of consolidation in the last mile of the delivery process that otherwise requires visiting many addresses and handling each parcel individually. Reducing the number of stops in the delivery route saves travel and handling time. Moreover, delivery to APLs will allow the delivery vehicle to follow the same tour at each delivery cycle, which makes the drivers' tasks more straightforward and less prone to errors. The APLs are typically located in easily accessible sites with suitable parking spaces for the delivery vans.

In some markets, when parcels are delivered to the recipient's address, it is customary that the parcels are left on the recipient's doorstep, while in others, they are handed to the recipient in person. In the former case, the APLs provide a much safer method of delivery that reduces the risks of theft and damage to the parcel by elements of nature. In the home-attended delivery case, using APLs saves the need to synchronize between the recipient and the courier. It eliminates the need for redeliveries in case the recipient is not available.

From the recipient's point of view, delivery to an APL may be preferred compared to home-attended or doorstep delivery for similar reasons, as it can be cost-effective. The APLs are also convenient for the delivery company and the recipients when there is a need to return a parcel. On the other hand, the method requires some effort from the recipient side because they need to go to an APL to pick up their parcels. Numerous studies that survey recipients of parcels indicated the potential acceptance of delivery through APLs and other self-collection facilities but stressed the importance of selecting appropriate locations for the APLs in the network. For some examples, see Iwan et al. (2016), de Oliveira et al. (2017), Caspersen and Navrud (2021), Molin et al. (2022), Rossolov (2023), Ozyavas et al. (2025), Ma et al. (2024), and Janinhoff et al. (2024).

The facility's location significantly affects the inconvenience of receiving a parcel through an APL. Suppose the network of the APLs is dense enough and designed with sufficient capacity such that an APL with an available locker can be found close enough to the recipient address. In that case, the inconvenience is likely to be minor. It should be noted, however, that a good set of locations for the APLs is determined not only by the coverage of all the recipient addresses within short distances. Other significant factors can be walkability and personal safety near the APLs. Moreover, an APL location is desirable to the recipients if it is adjacent to attraction points that many potential recipients patronize anyway.

Deploying an APL network in a region yields positive externalities that benefit parties beyond the delivery company and its customers. If properly designed, an APL network may reduce the traffic of motorized vehicles in the service area and save external costs such as congestion and emissions. For these merits to be materialized, the network should be designed to be more attractive for most recipients to walk or cycle to APLs rather than drive to them. In a city where a large share of the journeys are made by public transit, the APLs can be strategically located in public transit stations regularly attended by a large share of the population. In regions where most journeys are made by private cars, the abovementioned social merits of delivery by an APL network can be materialized if the APLs are located along the regular routes of most recipients, say, in gas stations and other drive-through facilities.

While the use of APL shares many common aspects with the use of attended service points (SPs), 24/7 automatic facilities create new opportunities for providing better and more consistent service at a lower cost. For these reasons, APLs are increasingly popular as a last-mile delivery method and, as of 2020, were used for about 12% of deliveries globally; see International Post Corporation (2020).

Deploying an APL network is a costly strategic investment. During the deployment phase, there is a high degree of flexibility in selecting the location and capacity of the facilities and determining the assortment of locker sizes at each APL. In this article, we describe the growing body of literature dealing with these strategic problems and point out significant gaps in the literature.

The problem of deciding on the location and other characteristics, such as capacity, of APLs in a parcel delivery network is a variant of the facility location problem that has been heavily studied in the last few decades. Section "General facility location and capacity models" presents several modeling approaches introduced in the literature for facility location problems. Next, in Section "APL location and capacity models," we present the recent literature on location models for APL networks in more detail. The surveyed paper presents models that capture some of the unique characteristics of parcel delivery networks.

The APL network may be owned and maintained by a single delivery company that utilizes it or by other commercial or public organizations that make the lockers of the APLs available for several potentially competing parties. In Section "Economies of scale and market structure," we discuss the economies of scale in the operation of APLs and their implications on the desired market structures of the parcel delivery industry.

General facility location and capacity models

The problem of selecting locations for service facilities to meet demand in a desirable way has existed for a long time, predating the emergence of APLs. In particular, the literature considers problems of covering service areas with various applications and objectives, such as attracting as many customers as possible to a chain of retail stores, reducing the total travel distances from warehouses that supply retailers or providing home-attended service, keeping walking distances of pupils to school short enough, maximizing the coverage of cellular networks, or reacting quickly enough to emergency calls by setting the locations of police, fire stations, and ambulances. Seminal works in this field are Maranzana (1964) and Manne (1964). For early surveys of this topic, see Owen and Daskin (1998) and the book Drezner and Hamacher (2004).

In a generic facility, location, and capacity problem, we are given a set of demand points, typically representative locations of a cluster of customers (say, a street block, zip code area, neighborhood, etc.). Each demand point is characterized by its total demand quantity per period. In addition, we are given a set of candidate facility locations. Each such location is characterized by a set of possible facility capacities that can be opened there, as well as the *fixed* cost of opening a facility in each possible capacity. Finally, we are given the *variable* cost of supplying one demand unit from each candidate location to each demand point. A solution to the problem prescribes the locations and sizes of the open facilities and the quantity supplied from each open facility to the demand point. The objective is to minimize the total fixed and variable costs.

The literature also describes other variants of the facility location problem aimed at different use cases. For example, there is an uncapacitated facility location problem in which each demand point can be served by its closest (or cheapest) open facility. Another variant is where the cost of opening a facility is subject to a budget constraint, and the objective is to minimize the variable costs. All the above problems generalized the set covering problem and thus NP-Hard.

Since facility location models aim to support strategic decisions that tie the organization's capital for an extended period, they must be based on simplifying assumptions about the nature of the demand and its evolution over the operational life of the deployed network of facilities.

A challenge in implementing any facility location and capacity model is forecasting the future demand and the future costs (of providing items from the open facility to the demand points and maintaining the open facility). The fixed costs are, in many cases, capital costs that are paid in advance. In contrast, the variable costs are accumulated over the system's operational time, which is typically unknown when the location decisions are made. Therefore, the solution is based on as accurate as possible estimations and assumptions that the planner makes.

More involved models also consider the demand's stochasticity and its expected evaluation over time. The latter calls for a model that allows facilities to be opened and expanded gradually over time.

The crucial challenge of forecasting the demand within the facility location and capacity problem, that is, considering spatial aspects of the demand, is largely overlooked. Some authors in the operation management literature assume that the demand is expected to grow uniformly and proportionally to the population's or the GDP's expected growth. Since accurate demand forecasts are seldom available, many facility location and capacity decisions are made incrementally based on the actual demand revealed over time.

APL location and capacity models

While the problem of selecting locations and capacities for a network of APLs is closely related to the models described in the previous section, some unique characteristics of this particular use case require the development of new models that were not studied before.

A comprehensive literature analysis presented in Mohri et al. (2024) conceptualizes APL systems based on the key stages, that is, plan, design, and evaluation. Location problems are part of the design stage. The paper investigates spatial distribution patterns for companies like Amazon lockers or China Post.

Deutsch and Golany (2018) were the first to formulate the problem of designing a network of APLs as a facility location model. For the strategic planning phase, they assumed that the capacity of the SPs is unlimited; therefore, parcels are always delivered via the closest open APL. In their model, the courier company provides monetary compensation to customers who need to travel a long distance to collect their parcels. Their model minimizes the total facility setup cost and the sum of the discounted compensation given to customers based on their travel distance. They show the model can be cast as a classical uncapacitated facility location model.

Rabe et al. (2021) formulated a deterministic multiperiod capacitated facility location model to plan an urban APL network's future development and expansion due to a forecast of the demand over a planning horizon of 10 years. In this model, additional APLs can be opened yearly, and existing APLs can be expanded with additional lockers. The APLs may serve recipients from their current district or neighboring ones for some penalty cost. Future demand scenarios were obtained from a system dynamic simulation model that was applied to generate demand growth scenarios that led to different plans for expanding the SP network. The level of service provided by the proposed system was evaluated using a simulation. The method was applied in a realistic setting in the city of Dortmund with 68 candidate SP locations.

Che et al. (2022) presented a multiobjective deterministic model for the location and capacity of APLs with the goals of minimizing the unsatisfied demand, the overlap between the coverage of opened SPs, and the total unused capacity of SPs. They present a genetic algorithm to solve this model.

Lin et al. (2020, 2022) studied a competitive uncapacitated facility location model in the context of a parcel delivery network under different discrete choice models. They presented an optimization model to select the set of locations for SPs in the presence of (static) competition from other player(s) in the market.

Grabenschweiger et al. (2022) study a location and routing model where APLs are used as an alternative for home delivery for some recipients. The goal is to minimize the cost over a known horizon, where the locations of the APLs are decided once, and the delivery routes are determined for multiple periods in advance. They present an effective mathematical formulation for the problem and a successful heuristic.

Mancini et al. (2023) formulate an SP location and capacity model as a two-stage stochastic problem with scenarios (Ω with $\omega \in \Omega$) of reduced APL capacity due to parcels that have not been picked up within a predefined time. In each scenario, the capacity of each SP is reduced by a quantity δ_j^{ω} that represents a temporal unavailability of the capacity of a set of locker boxes. The following decision variables and formulations are introduced.

- Y_{ij}^{ω}: binary variable indicating whether customer i is assigned to facility j in scenario ω or not
- Z_j: binary variable indicating whether a locker station is placed in location j or not

$$\max \sum_{\omega\in\Omega}\sum_{i\in I}\sum_{j\in J} Y_{ij}^{\omega} + \sum_{\omega\in\Omega}\sum_{i\in I}\sum_{j\in J}\frac{d_{\min}}{d_{ij}} Y_{ij}^{\omega}\frac{1}{|I||\Omega|} \tag{1}$$

$$\sum_{i\in I_s} Y_{ij}^{\omega} \le C - \delta_j^{\omega} \quad \forall\omega\in\Omega \;\; \forall s\in S \;\; \forall j\in J \tag{2}$$

$$\sum_{j\in J} Y_{ij}^{\omega} \le 1 \quad \forall i\in I \;\; \forall\omega\in\Omega \tag{3}$$

$$Y_{ij}^{\omega} = 0 \quad \forall\omega\in\Omega \;\; \forall(i\in I, j\in J|\phi_{ij}=0) \tag{4}$$

$$\sum_{\omega\in\Omega}\sum_{i\in I} Y_{ij}^{\omega} \le |I||\Omega|Z_j| \quad \forall j\in J \tag{5}$$

$$\sum_{j\in J} Z_j = P \tag{6}$$

$$Z_j \in \{0,1\} \quad \forall j\in J \tag{7}$$

$$Y_{ij}^{\omega} \in \{0,1\} \quad \forall i\in I \;\; \forall j\in J \;\; \forall\omega\in\Omega \tag{8}$$

The hierarchical objective function (1) combines the maximization of the number of customers assigned to locker stations with the minimization of the average distance covered by customers. Constraints (2) ensure that APLs' capacity is respected, while constraints (3) assigns each customer to at most one ALP in each capacity scenario. Compatibility is checked in constraints (4) and (5). The number of APLs to be installed is determined in constraints (6). Variable domains are defined in constraints (7) and (8).

A different but related stream of literature aims to design and evaluate the operation of Mobile APLs installed on vehicles or trailers that can serve multiple locations. Such mobile facilities can be autonomous or human-driven; see, for example, Schwerdfeger and Boysen (2022).

Xu et al. (2021) extend the problem by differing between unattended and attended facilities, which they denote as CDPs. Models for both variants of facility location problems are presented, and a data-driven method is proposed as a solution algorithm.

Kahr (2022) is the first (and the only by now) to present a model that simultaneously determines the location, capacity, and layout of the APLs. The layout in this context is the assortment of locker types in the APL, where each type can accommodate a particular type of parcel (e.g., small, large, refrigerated, frozen). Because the APLs are constructed from several types of standard modules of the same size and the number of modules at each location is restricted, the total number of possible layouts is finite.

It is assumed that a fixed fraction of the capacity of each APL became available every day. The demand is characterized by a set of scenarios. Parcels that do not fit in the available lockers within a given distance from the recipient location are not supplied via the system. The objective is to maximize the expected value of the supplied parcels over the demand scenario, which is equivalent to minimizing a sum of penalty costs for the parcels that are not supplied. The model is formulated as an integer linear program and solved using a Bender decomposition. Kahr (2022) demonstrated that his solution method is applicable for large-scale instances based on data collected in the three largest Austrian cities as long as the number of scenarios and the service radius are small.

Raviv (2023) solve the APL location and capacity problem, assuming a stochastic demand characterized as a discrete arrival process at each demand point. In addition, the author assumed that the number of delivery cycles until each parcel is collected (and its locker becomes available again) follows some known discrete distribution. The parcels of each demand point are supplied via the closest open APL. If there are no available lockers in the closet APL, parcels are either delivered directly to the address of the recipient or the delivery is postponed to the next cycle. Both of the above overflow events are subject to a given penalty cost. There is a small set of possible APL sizes, and a cost is associated with opening an APL at each particular size at the candidate location. The goal is to select locations and sizes for the APLs so as to minimize the total fixed and variable (penalty) costs. A preprocessing step calculates a function relating the total expected demand faced by each APL and its capacity to the expected penalty cost. A piecewise linear approximation of these functions is then embedded into a linear integer program that allows solving the stochastic APL location and capacity problem with a computational effort similar to that of the deterministic version. It is also shown that the obtained solution is significantly inferior when the problem is solved based on a reasonably large set of scenarios generated from the same distribution. Raviv (2023) adapted the Austrian cities dataset from Kahr (2022) and demonstrated that the presented solution method is viable for large-scale instances under a diverse set of problem parameters.

The parcel delivery process operation may influence the optimal locations and capacity of APLs. Specifically, if the operator has flexibility in prioritizing parcels, the network can achieve higher throughput. Sethuraman et al. (2024) suggest predicting the dwell time of each parcel in the locker before the recipient collects it. More lockers are reserved for parcels expected to be picked up sooner, which are prioritized for delivery. Notably, they found that parcels ordered through premium services, which guarantee shorter delivery times, are often collected faster. This prioritization allows for the better utilization of limited APL capacity. Given the potential impact of parcel allocation and prioritization policies on the performance of the APL network, future work should incorporate these factors into location and capacity models.

Economies of scale and market structure

An APL can be viewed as a queuing system with a single server. Parcels arrive at the APL according to a random discrete process, determining the number of new parcels at each replenishment cycle (say every day). Similarly, there is a random "service time," which is the number of cycles each parcel waits at the APL until it is picked. As mentioned above, a relatively early contribution to stochastic modeling of APL networks is due to Kahr (2022) and Mancini et al. (2023).

For simplicity, we assume here that when the capacity of an APL is exceeded, the parcels are delivered via another channel and have no effect on the future occupancy of their destination APL or any other APL in the network. With this simplifying assumption, we can view the APL as a loss queuing system with rejections. If we further assume that the pickup process is memoryless, the probability of a parcel being picked up between each of two consecutive delivery cycles is some fixed value, $p \in (0, 1)$. In Raviv (2023), it is demonstrated that this Markovian model is a good approximation for more realistic settings when the pickup probability of a parcel depends on its seniority and a parcel must be collected from the APL (or otherwise removed by the company) after a predefined number of cycles.

In the above Markovian model, the service rate (also known as the *offered load*) of an APL with C lockers is $C \cdot p$. The *load* (ρ) is the arrival rate divided by the offered load. Similarly, we can define a scale-free *rejection rate* as the expected number of parcels rejected at each period divided by the arrival rate.

In a fluid approximation of the system, no parcel is rejected as long as the offered load $\rho \leq 1$ and all excess load above 1 is rejected. The rejection rate is, thus, $min(0, \rho - 1)/\rho$ as depicted by the thick black line in Fig. 1; This is an asymptotic approximation of the system to which the actual rejection rate converges as the system size and the arrival rate increase proportionally. The other lines in Fig. 1 describe the rejection rate as a function of the load for systems with capacities of 30, 50, and 150.

In the APLs described in Fig. 1, the number of parcels that arrive at each replenishment cycle is a Poisson random variable with a rate parameter proportional to the APL capacity ($\rho = \lambda Cp$). An APL with a capacity of 150 can be viewed as 5 (resp., 3) APLs with a capacity of 30 (resp., 50) joined together. It can easily be observed from the figure that there is a strong pooling effect that renders small APLs to be much less effective than larger ones. For example, for five APLs that work under the load of $\rho = 0.8$ (i.e., $\lambda = 12$ for each), the rejection rate is 1.94%. If the five APLs are pooled together into one large ($C = 150$) APL that serves all their demand (i.e., $\lambda = 60$), the rejection rate will drop by two orders of magnitude to 0.02%.

Two important lessons for a planner of an APL network and policymakers are learned from the experiment summarized by Fig. 1: (1) APLs are subject to economies of scale, meaning that larger companies with more customers are likely to operate a much more efficient network of APLs; (2) Given total network capacity, in terms of the number of lockers, sparser networks with fewer but larger facilities can serve more demand.

We note that reducing the number of facilities also implies better consolidation of the parcels and shorter delivery routes. However, the fewer facilities are installed, the longer the distances of the APLs from the recipients (on average) and the less they will be inclined to use the system rather than order their parcel through a different service.

The implications for the delivery company are clear: It should deploy a network of APLs and use this mode of delivery only if the demand is high enough to justify reasonably large APLs while still allowing a dense enough network to provide a convenient service.

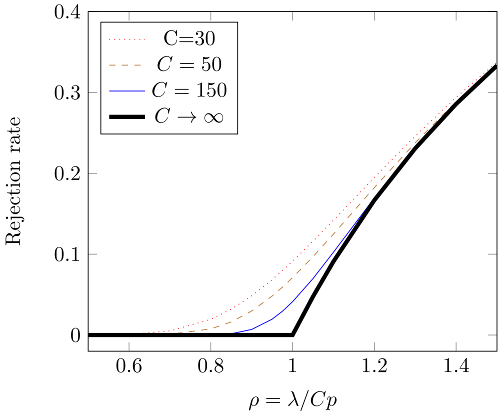

Fig. 1 Economics of scale (Poisson arrivals with pickup probability $p = 0.5$).

The first step would be to analyze the population density in the service area and to conduct market research to evaluate the expected penetration of the delivery by APLs.

In the short run, delivery companies can economize their network by collaborating with their competitors and exchanging or leasing excess capacity on an ad hoc basis. However, long-run business considerations may cause them to avoid such collaboration, particularly with small firms, to drive them out of the market.

Policymakers should consider the fact that, due to the economies of scale, there is a natural monopoly in providing parcel delivery service through an APL network. If they wish to materialize the economic and environmental benefits of such a delivery mode in their jurisdiction, they should take regulatory measures that will foster it. A sound policy is enacting a regulation that separates the delivery business from the ownership and management of the APL network.

An effective market structure can be when one or a couple of firms are chartered to deploy an APL network in a geographical area, and this firm is obliged by the regulation to allow all the delivery companies to use it for a fair fee charge based on their usage volume. Such a market structure allows the development of a dense and efficient network of APL, lowers the entrance barrier for new delivery companies to enter the market, and thus enhances the competition and increases the consumer surplus and the market size, hopefully at the expense of the less desirable home delivery mode. Similar regulations can be found in many communication markets when there is a regulatory separation between the infrastructure and the content provider.

Behavioral aspects of service point locations

In the models reviewed in this survey, it is commonly assumed that a set of candidate locations for the SPs is given as input for the location model and that the implications of setting up an SP in each of these in terms of cost and quality of service are quantified and known. However, recent literature suggests that the recipients' preferences and behavior are affected significantly and intricately by the characteristics of the particular selected locations. These characteristics may affect the perceived level of service and, consequently, the decision of the recipients to use the network (rather than opting for home delivery, for example) and the choices that the recipients make when using the system. All of these have implications and the optimal design and operation of the SP network for parcel delivery that is largely overlooked (or abstracted) by the facility location literature.

Lemke et al. (2016) were the first to study behavioral aspects and preferences of parcel recipients using an SP network. They base their conclusion on extensive user surveys among recipients in Poland. Other researchers continue this line in different cultural settings, for example, Schaefer and Figliozzi (2021). Important considerations for selecting potential locations are analyzed in Lagorio and Pinto (2020) and Faugere and Montreuil (2016).

Unsurprisingly, many studies found that the proximity of the collection point to the recipient's address strongly affects their preferences (Iwan et al., 2016; de Oliveira et al., 2017; Caspersen and Navrud, 2021; Molin et al., 2022; Rossolov, 2023). Other influencing factors are opening hours (Iwan et al., 2016; Giuliano et al., 2022; Molin et al., 2022), availability of parking, and proximity to other locations visited by the recipients allowing them to collect their parcels on the go (Iwan et al., 2016; de Oliveira et al., 2017). Several studies such as Caspersen and Navrud (2021), Molin et al. (2022), and Rossolov (2023) suggest that demographic features of the recipients may also influence their delivery preferences. Iwan et al. (2016), de Oliveira et al. (2017), and Giuliano et al. (2022) noted safety concerns of the pickup location as a significant factor that strongly interacts with the gender of the recipients.

Hofer et al. (2020) looked into the mobility behavior of recipients who walk, cycle, use public transport, or drive to collect their parcels from APLs. They found that the recipients are willing to travel 7–10 min to distances of up to 3.6 km, depending on their means of transportation. Mitrea et al. (2020) found that most consumers are willing to deviate by at least 5 min from their regular commuting routes to collect their parcels in an APL.

It should be acknowledged that different surveys were concentrated in different cultures and geographies and where delivery options are available. However, a substantial diversity in the recipients' preferences was observed within each studied population, which we believe calls for personalizing the delivery process.

Ma et al. (2022) stressed the importance of planning the delivery process to APLs (and other parcel self-collection points) while both operational aspects and recipient preferences are considered.

Few studies addressed the possibility of recipients expressing their preferred delivery pickup locations, which would allow the delivery company to consider them when planning its operation and assigning parcels to lockers. Orenstein et al. (2019) assumed that recipients specify multiple alternative destinations when placing orders. These locations need not necessarily be close to each other and can represent locations near the recipient's home, workplace, or commuting route. The company then utilizes this flexibility to plan efficient delivery routes and parcel assignments to lockers. Dragomir et al. (2022) and Escudero-Santana et al. (2022) assumed that the recipients' flexibility is expressed in terms of location and time. That is, the recipient can specify several alternative locations and associated times for the delivery. They formulate and solve the resulting vehicle routing problem with flexible delivery locations and time windows.

However, we are unaware of any study incorporating user preference considerations other than those directly related to the distance from the recipient's home address in the strategic planning phase when determining the location and capacity of the SPs.

Conclusion and outlook

All the papers reviewed in the previous section made some restrictive assumptions regarding the system's operation. They all took the point of view of a single company that wished to use the network to economize its operations and gain a competitive advantage. The APL's state-of-the-art literature on planning networks is still missing much-needed tools and insights.

In practice, APL networks can provide many benefits that the current models in the literature overlook. In particular, an APL network shows strong economies of scale and economies networks, with pooling effects within large APLs and neighboring APLs in a dense network. A more detailed operational model and more accurate information about recipient preferences are required to plan the network correctly.

Suppose, for example, some recipients are less sensitive to the distance they walk to the APLs. Then, it may be possible to deploy a sparser network with larger APLs that better exploit the pooling effect and are less likely to run out of available lockers. Similarly, suppose other recipients are less sensitive to the delivery time. In that case, this may impact the optimal locations and capacity of the APLs, which may be particularly significant if the delivery company can reveal these preferences, possibly by offering some incentives.

Similarly, suppose the delivery company can divert some of the demand between neighboring APLs or incentivize recipients to collect their parcels more quickly from congested APLs. In that case, it may achieve an effect similar to a short-term extension of the APLs' capacity.

An interesting research question with practical implications is how to determine the desired density of the system. Is it better to have a network with many small APLs or one with fewer larger APLs? The former may reduce the recipients' average walking distance but requires their flexibility and willingness to obtain parcels at various APLs in their vicinity or alternatively to wait until the closest APL to their location becomes available.

The optimal structure of an APL-based network is likely influenced by the characteristics of the area it serves. Specifically, different considerations should be applied in dense urban environments, which are well-served by public transit and have strong cycling and walking infrastructure, compared to sparsely populated areas. In dense cities, APLs should ideally be located within short walking distances, offering comprehensive coverage to both residential and employment zones. In contrast, in less populated areas, APLs must be positioned at locations accessible from major traffic arteries, for example, in gas stations. Research on this topic, which lies at the intersection of geography, urban planning, and operations management, is much needed.

Another important aspect from a practical point of view is planning the system's expansion over time by opening new SP locations and extending the capacity of the current location. A simple approach toward this challenge is to adapt the models presented in this chapter to facilitate incremental changes based on an existing network layout in the face of current demand patterns. A more profound approach is to develop a multiperiod model that accepts a long-term demand forecast as input and plans the system's gradual expansion over these periods.

A new technology is to use Mobile APL. Schwerdfeger and Boysen (2022) describe the different concepts of such locker. The lockers can be either mounted on a vehicle or unloaded and left in predetermined locations, and the vehicle may be autonomous or driven by a human driver. An interesting location and capacity problem to be studied is how to design a network of stationary APLs where it is possible to meet overflow demand using such mobile APLs.

It is also essential to understand the effect of possible communication between the recipients and the delivery company regarding their preferences based on the current availability of the lockers in the system.

From a social point of view, it is essential to understand how the parcel delivery market should be regulated. In most countries, the delivery companies own APLs and may allow their competitors and collaborators to use them for a fee. Since there are clear economies of scale

Takeaways for operation managers

For operations managers designing and developing automated parcel delivery lockers networks, a key takeaway from this chapter is that planning should be grounded in accessible data, such as regional demographics and historical demand for delivery services. The planner must weigh the trade-off between a network with fewer, larger facilities and one with more, smaller facilities. While the former benefits from higher efficiency due to the pooling effect and shorter courier routes, the latter offers better accessibility for recipients, potentially increasing the market share of this delivery method. Additionally, the economies of scale and network effects emphasize the advantages of collaboration among competing courier firms operating in the same area, underscoring the need for government regulation or even direct intervention in the industry.

Takeaways for researchers

While the literature on location models is well-established, significant gaps remain in the research on designing APL networks for parcel delivery. In particular, there is limited understanding of demand patterns for parcel collection based on demographic and historical commercial data. More research is needed to model recipient preferences' spatial and temporal aspects. Additionally, case studies on APL network deployment from industry can help bridge the gap between scientific theory and practical operations.

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