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Mobile parcel lockers with individual customer service

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Abstract

The ongoing growth of e-commerce deliveries has led to a significant increase in last-mile delivery volumes. New technologies are being investigated to provide these deliveries efficiently and in a customer-friendly manner. A common practice is to use fixed parcel lockers (FPLs) to make deliveries independent from the presence of the customer as is the case in attended home deliveries (AHDs). FPLs are usually installed at key locations in cities, and customers can collect their package at any time once it has been delivered to this particular location. Mobile parcel lockers (MPLs) represent a new idea: they can be parked for temporary collection of items at different locations, keeping the pickup distance to the customer short and avoiding high infrastructure costs. However, customers need to collect their parcels within a restricted time window. This service is supposed to become especially efficient through autonomously operating vehicles that can move MPLs at low costs. In this article, we introduce the heterogeneous locker location problem to study the effects of fleets combining two of the services—FPLs, MPLs, AHDs—within one framework. In our comparison, we consider that customers may have different expectations regarding their maximum pickup distance as well as their temporal flexibility in accepting deliveries. A fixed fleet is applied to maximize the number of customers served, respecting individual customer preferences in terms of pickup distances and time windows. We evaluate the different delivery services regarding managerial insights on service quality and efficiency. In the experiments, we analyze the impact of structural demand differences and different fleet sizes, as well as the operational fleet utilization and the individual customer experience. Results show the potential to increase the number of customers served by about 14%–19% through the use of MPLs while considering individual customer preferences.

KEYWORDS

attended home delivery, customer preferences, heterogeneous locker location problem, individual customer service, last-mile delivery, mixed-integer program, mobile parcel locker, parcel locker

1 | INTRODUCTION

Last-mile operations are the most challenging factor in terms of costs and planning when delivering goods to private customers [12]. Traditionally, customers have received deliveries directly at home, which is very convenient but involves uncertain arrival times and relatively high costs for logistics service providers. Consequently, the customer may not be present for accepting a delivery, which can result in failed deliveries and in further delivery attempts. Therefore, customers and logistics service providers are increasingly planning *attended home deliveries* (AHDs) through delivery time windows. This reduces the risk of failed deliveries and enables customers to plan their daily schedules more flexibly [10]. Besides these advantages, providers are restricted in their tour planning. For a survey on AHD related problems, the interested reader is referred to Dixit et al. [3] or Kumar and Panneerselvam [14].

To avoid the high cost of deliveries and failed deliveries, another common way of last-mile services is *fixed parcel lockers* (FPLs), which are filled by the logistics provider regularly, for example, once every morning. FPLs promise a flexible pickup time for the customer, lower costs for logistics service providers [20], a positive impact on ecological sustainability [5], and the possibility to manage the constantly increasing transportation volume better [26]. From a customer perspective, on the one hand, the customer has the advantage of being able to plan his or her daily schedule more flexibly; on the other hand, he or she needs to become active and travel to the parcel locker for pickup. A study by McKinsey showed that 70% of customers prefer low-cost delivery, but prefer home delivery to parcel lockers if the costs are the same [12]. For the provider, detours and failed deliveries are minimized. However, the decisive factors for the efficiency of FPLs are their location and capacity, which are determined by strategic planning [2, 7, 9].

A new and innovative service is provided by *mobile parcel lockers* (MPLs), which can change their location with or without a driver [19]. In research and everyday life, this service has not received much attention yet. Some practical trials can be observed, for example, by the postal service in Poland [11] or by a start-up in Berlin, Germany [13]. Compared to the established FPLs, MPLs do not require an extra filling tour but can be filled directly at the depot. In addition, while the long-term planning of FPLs is associated with high initial investments, MPLs can be repositioned as often as required and therefore adapt to the current customer demand. However, for MPLs, the customers are given a certain time window to pick up their parcels. In contrast to AHDs, where short time windows are often preferred, it can be assumed that a longer time window is better for the customers when being serviced via MPLs, as it allows greater self-determination and flexibility. While MPLs are not prevalent neither in the real world nor in the literature yet, they are an attractive last-mile transportation mode as they combine the consolidation advantage of FPLs with the flexibility of AHDs.

As MPLs, FPLs, and AHDs show different characteristics, in this article, we present the heterogeneous locker location problem (HLLP) to study the effects of fleets combining two of the services. Similar to Schwerdfeger and Boysen [18], we also consider the services separately, but in contrast we study the operational problem of serving customers with a given fleet and analyze the effects of different fleets on service quality and delivery efficiency.

We compare last-mile deliveries with FPLs to a fleet of MPLs and to a fleet of AHD vehicles. We also investigate all combinations of two of these services to accommodate individual customer preferences. The combinations seem promising, as AHDs and FPLs represent two very different services: for AHDs, no pickup efforts are required, but delivery time windows can be very restrictive. FPLs reduce costs and increase flexibility, but require some pickup efforts by customers. MPLs as a new variant offer a blend of both features and can operationally adapt for a more diverse and efficient service.

We assume that customers have individual requirements regarding flexibility, and we try to accommodate these requirements as logistics service providers. We consider two types of customers with different levels of willingness to pick up their item (reflected by the allowed maximal distance to the pickup location) and with varying pickup flexibility (reflected by the length of pickup time windows). We evaluate the efficiency of the different services by means of the number of customers served and by how well we can accommodate the different customers' expectations.

Our contributions to the literature are as follows. First, we introduce the HLLP that maximizes the number of customers that can be served with a given fleet of service vehicles, where the fleet may consist of different types of service vehicles and where customers have individual preferences. Second, we analyze the effects of different service fleets on the achieved service level. While we cannot assess the investment costs of the new MPL technology, we particularly focus on managerial insights for a service provider as we analyze the service level for different customer types and fleet mixtures.

Section 2 summarizes the literature related to the considered delivery services. The HLLP is described in Section 3. Then, a mathematical model is presented and implementation details are discussed in Section 4. The design of the experiments and the results are presented in Section 5. We conclude in Section 6.

2 | RELATED LITERATURE

While the problem considered in this work is related to several other problem settings, this section primarily focuses on literature dealing with parcel lockers in an operational setting and the integration of customer preferences. The most relevant papers are listed in Table 1. Which types of delivery "services" were included in each study is marked with [+]. In "locations per customer," it is indicated how many delivery locations a customer can specify. In the case of MPL, the pickup distance is used to determine whether a customer can be served at a particular location. Whether the pickup efforts are individual ([yes]) or the same for all customers ([no]) is shown in the "individ. MPL pickup effort" column. Customers specify either "no" time

TABLE 1 Literature comparison.

Research studies	Services: Single AHD	FPL	MPL	Combination FPL &MPL	AHD &FPL	AHD &MPL	Options: Locations per customer	Individ. MPL pickup effort	Windows per customer	Individ. window lengths	Solution
Orenstein et al. [17]		+					Any	–	None	–	H
Veenstra et al. [23]					+		One	–	None	–	E/H
Enthoven et al. [6]	+				+		One	–	None	–	H
Mancini and Gansterer [16]					+		One/two	–	One	No	(M)H
Grabenschweiger et al. [9]					+		Any	–	One	Yes	H
Dumez et al. [4]	+				+		Any	–	Any	Yes	H
Tilk et al. [22]					+		Any	–	Any	Yes	E
Schwerdfeger and Boysen [18]		+	+				Any	No	Any	Yes	E
Schwerdfeger and Boysen [19]		+	+				Any	Yes	Any	Yes	H
Wang et al. [24]				+			One	No	One	Yes	(M)H
Wang et al. [25]				+			One	No	None	–	E
This work	+	+	+	+	+	+	One	Yes	One	Yes	E

window at all or "any" number of time windows, which is given in the column "windows per customer." If time windows are considered, the lengths are individual for different customers or the same for all customers, as indicated in the column "individ. window lengths." The last column "solution" indicates whether the applied solution methods are of exact "[E]," heuristic "[H]," or matheuristic "[(M)H]" nature.

Orenstein et al. [17] investigate FPLs in the context of customers selecting multiple locations and assigning priorities for delivery options. Several papers address the integration of FPLs and AHDs. In the medical field, Veenstra et al. [23] let the logistics service provider choose the mode of delivery, that is, whether to deliver via AHD or by FPL, which implies opening costs. Enthoven et al. [6] investigate a case where customers can choose between home delivery or FPL in a two-echelon system. Mancini and Gansterer [16] add time windows and the third option that the customer would accept deliveries both via FPL and AHD. Grabenschweiger et al. [9] always allow AHDs while the customers can specify several FPL locations as alternatives. The next extension is introduced by Dumez et al. [4] and Tilk et al. [22], where multiple locations can be provided with time windows and individual delivery location priorities.

Schwerdfeger and Boysen present the idea of MPLs for the first time in [18] and address various realization concepts in [19]. Schwerdfeger and Boysen [18] allow customers to specify multiple locations with time windows. They evaluate the required fleets to serve all customers with only FPL or MPL, respectively, for different pickup efforts. In [19], driver assignments and incurred costs are incorporated to investigate different MPL concepts, such as mounted or loaded and fixed drivers, swap drivers, or autonomous driving. Wang et al. [24] consider a pickup and delivery problem, where customers are served using either FPLs or MPLs. They consider single customer locations and add pickup services to the delivery problem. This work has been further extended to incorporate stochastic demand in [25].

Recently, individual customer preferences have become more important in the context of last-mile deliveries. For instance, customers can now define several delivery options [9, 16, 18, 22] and even assign individual priorities to these options [4, 17]. In this article, however, we assume that a customer does not want to provide his or her entire daily schedule to the provider. Instead, the customers have precise but individual preferences as to when they want to be served, over what length of time, and with how much pickup effort.

We introduce the HLLP to integrate FPL, MPL, and AHD services into a single problem. We maximize the number of customers served, for a given fleet, respecting individual customer preferences. This enables a fair comparison of how the single and combined services perform in different situations regarding structural demand and customer preferences. In order to efficiently address our customers' preferences, we consider six variations of services, namely the three single services FPL, MPL, and AHD, as well as the combinations FPL&MPL, AHD&FPL, and AHD&MPL. With this work, we therefore contribute to the literature by considering not only single services or the AHD and FPL combination, but additionally the MPL combinations. Further, we consider individual customer preferences regarding the individual pickup effort.

3 | HETEROGENEOUS LOCKER LOCATION PROBLEM

In this section, we present the HLLP that incorporates not only different types of delivery services but also considers individual customer preferences. The aim is to serve as many customers as possible with a given set of delivery resources considering the technological constraints and individual customer preferences. Customer preferences are represented by spatio-temporal restrictions. For spatial restrictions, each customer has a maximum pickup distance from the customer's home to a pickup location, reflecting the maximum individual effort the customer is willing to invest for a pickup. For temporal restrictions, a customer specifies when and over what length of time the pickup or delivery should occur. We assume the service provider knows the customer preferences perfectly.

The services we investigate are AHDs, FPLs, MPLs, and any combination of two of these. The first is found in the majority of the literature and corresponds to established industry practice. Here, a vehicle with a driver handles the delivery to the customer within a specified time window. The second are FPLs, which do not move and have exactly one location where customers can pick up their delivery as soon as it is available. Contrasting FPLs, MPLs are parcel lockers which can change their location during the day. The MPLs stop within reach of the customers so that they can pick up their delivery at any time within their desired pickup time window. An MPL service can be carried out in a variety of ways. Schwerdfeger and Boysen [19] compare the costs when the MPLs are realized with a driver, autonomously or as a trailer.

Figure 1 shows examples of problem realizations for FPLs, MPLs, and AHDs with one single (fixed) locker or truck. The four customers have an individual maximum willingness of pickup effort (indicated by the pickup radius) and expect deliveries in individual customer time windows (indicated by the time window). The FPL has one dedicated location for pickup, which is not reachable by one customer due to the restricted pickup distance. The MPL has four predefined parking locations to potentially perform stopovers. In the solution, two stopovers are chosen to reach all customers and fulfill their time window constraints. These stopovers are defined by a parking location and a period of time. AHD simply visits each of the customer locations in their respective time windows. In the end, AHD and MPL can serve all customers—AHD with four stopovers and MPL with two stopovers—and FPL can serve three customers. To illustrate one possible combination of services: if FPL and AHD operate together, AHD can, for example, serve customers who could not be reached via FPL, as shown in Figure 2.

To solve the HLLP, we exploit that each service can be modeled as a vehicle that stops at different locations for a different amount of time, following a feasible routing schedule. In this way, we can represent all services simultaneously in the model with only minor changes, that is, we refer to all vehicles as lockers that operate in a specified "mode". For each locker, the solution includes a series of stopovers to be made in order to maximize the number of customers served. In the case of combinations, the optimal solution will determine which customers should be served with which of the available service modes.

In the simplest case, FPLs "stop" at one location for the whole day. MPLs can stop at several locations multiple times for an indefinite period of time. AHDs stop only once at each location for exactly the same relatively short period of time. FPLs and MPLs can serve many customers at the same time from one location, whereas AHDs serve each customer individually. However, AHDs have a rather short service time to hand over the delivery, whereas MPLs have to be available for a longer period of time in order to allow the customers to pick up the deliveries.

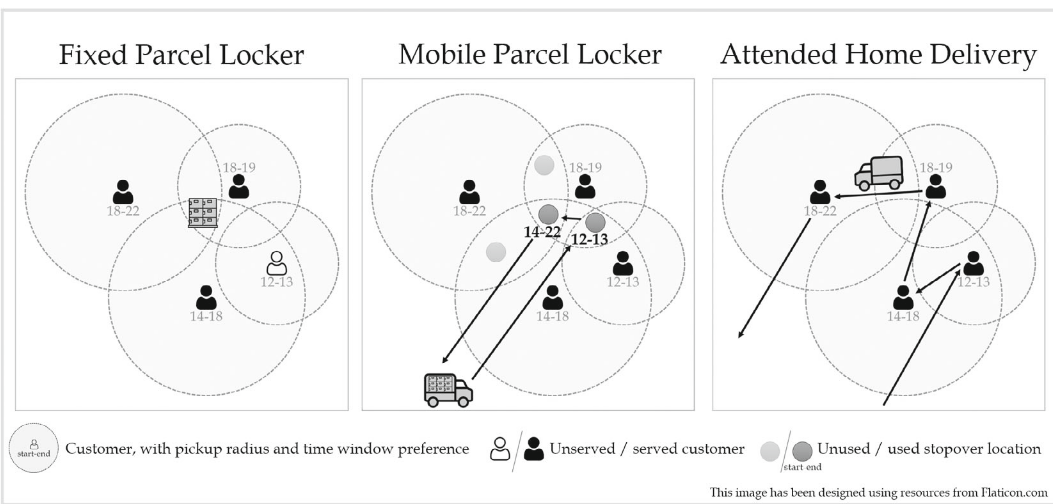

FIGURE 1 Example for FPL, MPL, and AHD.

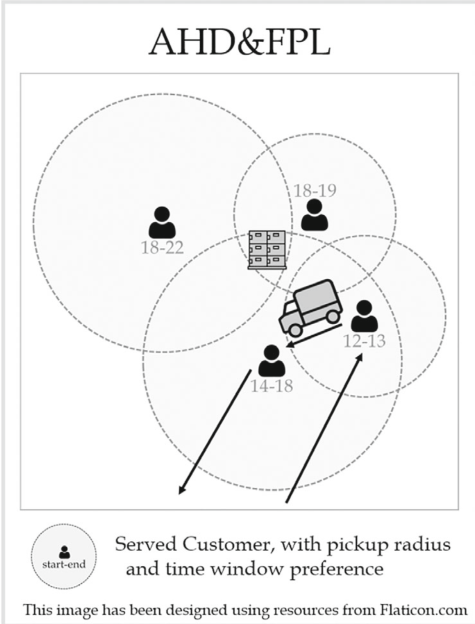

FIGURE 2 Example for the combination of AHD and FPL.

Schwerdfeger and Boysen [18] discuss conceptually similar problem settings such as the location routing problem and present the time discretization-based mobile locker location problem. The discrete-time approach is closely related to the HLLP and helps to find a representative solution in a suitable time. However, their problem focuses on the optimal fleet size from a strategic perspective. We need to adapt it to the HLLP, which analyzes the operational perspective with predefined fleets. We consider customers with individual preferences, which includes having the parcel lockers available to the customer for the entire pickup time window to allow the desired flexibility, which is different from the current literature. Furthermore, we add the functionality to handle lockers of multiple modes and let the model choose the optimal allocation of customers by efficiently using the available resources.

4 | MATHEMATICAL MODEL

The problem described in Section 3 can be formalized as a Mixed Integer Program (MIP). The most important concepts are the modes, the stopovers, and the drives. Each locker is assigned to a mode, such as FPL, MPL, or AHD. Stopovers and drives are time-discrete characteristics that describe all possibilities of the lockers to perform actions. If a locker is assigned to a stopover, it is specified that the locker remains at the location of the stopover from the start time of the stopover until the end time of the stopover. In addition, the assigned drives describe the movements between the stopovers. In the HLLP, lockers are only allowed to use stopovers and drives that match the locker mode. In addition, the locker fleet is fixed and the number of customers accepted is to be maximized.

4.1 | General model

In the following, we provide a detailed explanation of the MIP and then address its parameterization for different locker modes. The required sets and parameters are summarized in Table 2. All locations p which are available for a stopover independent of the temporal restrictions are contained in the set P. In addition, γ represents another location at which each route of a locker must start and end. This could be a depot location, but in the following we consider a pseudo location to initialize the locker without travel time.

The spatial and temporal assignment of the locations is realized by the stopovers. The set S contains all relevant possibilities to perform a stopover. Each stopover $s \in S$ is represented by a specific stopover location p_s^S, a stopover start time $\underline{t}_s^S$, a stopover end time $\overline{t}_s^S$, and a stopover mode m_s^S. The mode represents the restriction that a stopover can only be used by a locker type of the corresponding service, that is, FPL, MPL, or AHD.

The possibility to move from one stopover to another stopover is expressed by the drives. A drive d of the set of drives D is represented by a drive mode m_d^D, a drive start location $\underline{p}_d^D$, a drive end location $\overline{p}_d^D$, and a drive time t_d^D, which specifies when the locker departs from the start location. Besides drives between stopovers, additional drives to and from the location γ have to be defined to enable a complete tour. For each $p \in P$, drives from γ with arrival corresponding to $\underline{T}_p^{S\gamma}$ and drives to γ with

TABLE 2 Sets and parameters.

$p \in P$	Set of available parking locations
γ	Pseudo (depot) location, representing start and end of a tour
$s \in S$	Set of stopovers, for each exists: mode (m^S), parking location (p^S), start time ($\underline{t}^S$), and end time ($\bar{t}^S$)
m_s^S	Mode of stopover s
p_s^S	Parking location of stopover s
$\underline{t}_s^S$	Start time of stopover s
$\bar{t}_s^S$	End time of stopover s
$d \in D$	Set of drives, for each exists: mode (m^D), starting location ($\underline{p}^D$), final location ($\overline{p}^D$), and departure time (t^D)
m_d^D	Mode of drive d
$\underline{p}_d^D$	Parking location where drive d starts
$\overline{p}_d^D$	Parking location where drive d ends
t_d^D	Departure time of drive d
$\sigma_{\underline{p},\overline{p},t}$	$\sigma \in \mathbb{Z}$ is the departure time at $\underline{p}$ to arrive in $\overline{p}$ at time t
$t \in T$	Set of discrete points in time
$\underline{T}_p^S$	Set of subsets of T where a stopover-start exists at parking location p
$\overline{T}_p^S$	Set of subsets of T where a stopover-end exists at parking location p
$\underline{T}_p^{S\gamma}$	Set of subsets of T where a stopover-start exists at parking location p, where no prior stopover exists at p - enables a possible start drive, from γ
$\overline{T}_p^{S\gamma}$	Set of subsets of T where a stopover-end exists at parking location p, where no successive stopover exists at p - enables a possible end drive, to γ
$c \in C$	Set of customers
$b_{c,p,\underline{t},\bar{t}}$	$b \in \{0,1\}$ indicates if a customer c can be served by a stopover with: $p, \underline{t}, \bar{t}$
$l \in L$	Set of lockers, for each exists: mode (m^L) and capacity (κ)
m_l^L	Mode of locker l
κ_l	Capacity of locker l

departure corresponding to $\overline{T}_p^{S\gamma}$ are created. In addition, the parameter $\sigma_{\underline{p},\overline{p},t}$ indicates the departure time of a particular drive which starts from $\underline{p}$ and arrives on time t at $\overline{p}$.

The complete time horizon is given in the set T, which contains all discrete points in time. For example, with a time horizon of 1:00 to 5:00, discretized in 1 h intervals, T contains {1:00, 2:00, 3:00, 4:00, 5:00}. For each available location $p \in P$, one subset of T represents the times at which at least one stopover starts $\underline{T}_p^S$ and at least one stopover starts that does not have a prior stopover at the same location $\underline{T}_p^{S\gamma}$. In the same way, $\overline{T}_p^S$ represents points in time at which at least one stopover ends and $\overline{T}_p^{S\gamma}$ when at least one stopover ends that does not have a subsequent stopover at the same location. The customers c are given in set C. The binary parameter $b_{c,p,\underline{t},\bar{t}}$ indicates whether it is possible to serve a customer c by a stopover at location p in the time interval $\underline{t}$ to $\bar{t}$. Finally, the lockers are defined by the set L and each locker l has a mode m_l^L and a capacity κ_l.

Based on the given parameters, three decisions are made. The variable $y_{l,c}$ decides if customer $c \in C$ should be served by locker $l \in L$. The two remaining decisions are which stopovers $x^S_{l,p,\underline{t},\bar{t}}$ and which drives $x^D_{l,\underline{p},\overline{p},t}$ are used by the respective lockers $l \in L$. The mathematical model is as follows.

$$\max \sum_{l \in L} \sum_{c \in C} y_{lc}, \tag{1}$$

$s.t.$

$$\sum_{l \in L} y_{l,c} \leq 1 \qquad \forall c \in C, \tag{2}$$

$$\sum_{c \in C} y_{l,c} \leq \kappa_l \qquad \forall l \in L, \tag{3}$$

$$\sum_{\substack{s \in S \\ m_s^S = m_l^L}} b_{c,p_s^S,\underline{t}_s^S,\bar{t}_s^S} * x^S_{l,p_s^S,\underline{t}_s^S,\bar{t}_s^S} \geq y_{lc} \qquad \forall l \in L, c \in C, \tag{4}$$

$$\sum_{\substack{s \in S \\ m_s^S = m_l^L \\ p_s^S = p \\ \underline{t}_s^S = \underline{t}}} x^S_{l,p,\underline{t},\bar{t}_s^S} = \sum_{\substack{d \in D \\ m_d^D = m_l^L \\ \overline{p}_d^D = p \\ t_d^D = \sigma_{\underline{p}_d^D,p,\underline{t}}}} x^D_{l,\underline{p}_d^D,p,t_d^D} \qquad \forall l \in L, p \in P, \underline{t} \in \underline{T}_p^S, \tag{5}$$

$$(6) \quad \sum_{\substack{s\in S\\ m_s^S=m_l^L\\ p_s^S=p\\ \bar{t}_s^S=\bar{t}}} x^S_{l,p,\underline{t}_s^S,\bar{t}} = \sum_{\substack{d\in D\\ m_d^D=m_l^L\\ \underline{p}_d^D=p\\ t_d^D=\bar{t}}} x^D_{l,p,\overline{p}_d^D,\bar{t}} \qquad \forall l\in L, p\in P, \bar{t}\in \overline{T}^S_p,$$

$$(7) \quad \sum_{p\in P}\sum_{t\in \overline{T}^{S_\gamma}_p} x^D_{l,p,\gamma,t} \le 1 \qquad \forall l\in L,$$

$$(8) \quad y_{l,c}\in\{0,1\} \qquad \forall l\in L, c\in C,$$

$$(9) \quad x^S_{l,p,\underline{t},\bar{t}}\in\{0,1\} \qquad \forall l\in L, p\in P, \underline{t}\in T, \bar{t}\in T,$$

$$(10) \quad x^D_{l,\underline{p},\overline{p},t}\in\{0,1\} \qquad \forall l\in L, \underline{p}\in P\cup\{\gamma\}, \overline{p}\in P\cup\{\gamma\}, t\in T.$$

The objective function (1) maximizes the number of customers that are served by the available locker capacity. Constraint (2) ensures that each customer is served at most once. Each locker can serve a maximum of customers according to its capacity (3). For a customer to be served by a locker, the locker must stop at a compatible stopover according to the customer's location and time window preferences. Whether a customer and a location are compatible in a certain time window is identified by the parameter b. In addition, the locker must also be compatible with the stopover according to its delivery mode. Constraint (4) checks these compatibilities. Constraints (5) and (6) represent the flow conditions, that is, if a locker uses a stopover, it must also drive to and from this stopover. To ensure that each locker is used only once, (7) limits the number of drives of a locker to the pseudo location γ to a maximum of 1. The binary decision variables are defined in the Equations (8)–(10). Constraint (8) defines which locker $l\in L$ serves which customer $c\in C$; (9) defines at which stopover of S a locker l dwells; and Constraint (10) represents which drives of D a locker l uses. In Constraints (9) and (10), stopovers and drives are associated with each other following their unique properties regarding location and time window.

4.2 | Model adaptations for FPL, MPL, AHD

In the HLLP, each locker is operated in one of the three modes FPL, MPL, or AHD. The stopovers as well as the associated drives belong to a certain mode, which expresses that they can be used by lockers of the same mode. In the following, we discuss how the available stopovers and drives are defined for the different modes and which customers can be served by a specific stopover.

For FPL, one stopover is created at each FPL location $p\in P_{FPL}\subseteq P$. These stopovers start at the earliest possible working time $\underline{w}$ and end at the latest possible working time $\overline{w}$ according to the considered time horizon. Hence, for each FPL location $p\in P_{FPL}$, we create a stopover (FPL, p, $\underline{w}$, $\overline{w}$), which means a stopover usable by lockers in FPL mode, at location p from $\underline{w}$ to $\overline{w}$. Since these lockers are permanently located in one place, no drives are needed, except for the start and end at the pseudo location γ for all available locations. Moreover, to define the parameter b, the maximum pickup distances need to be checked for each customer and stopover combination. As each FPL stopover persists the entire time horizon, the customer time windows do not need to be verified.

For MPL, at each MPL location $p\in P_{MPL}\subseteq P$, multiple stopovers are created in the considered working time horizon ($\underline{w}$ until $\overline{w}$) according to the discrete time interval z. This means that we create a stopover (MPL, p, *start*, *end*) for each $p\in P_{MPL}$ with *start* as an element from the set of $\underline{w}$ to $\overline{w}-z$ with z interval steps and *end* as an element from the set of *start* $+\, z$ to $\overline{w}$ with z interval steps. For example, with $\underline{w}=$ 1:00, $\overline{w}=$ 4:00 and $z=1$ h, the time windows at any given location would be {1:00–2:00, 1:00–3:00, 1:00–4:00, 2:00–3:00, 2:00–4:00, 3:00–4:00}. In addition to the drives from and to the pseudo location γ, further drives will be created between two stopovers whenever they can be reached in time. Travel times are rounded up to the next discrete point in time. In order for a customer to be served by an MPL stopover, the location must be accessible within the allowed pickup distance, and the customer time window must be within the stopover time window.

For AHD, the stopovers are defined differently than those for MPL. In this context, the potential AHD locations are the customer locations. Hence, at each AHD location $p\in P_{AHD}\subseteq P$, the earliest possible time $\underline{w}_{c(p)}$ and latest possible time $\overline{w}_{c(p)}$ are now determined by the associated customer time window. According to the discrete-time interval z, the stopovers are defined exclusively within this customer time window ($\underline{w}_c$ until $\overline{w}_c$). Thus, stopovers (AHD, p, *start*, *end*) are created for each $p\in P_{AHD}$ with *start* as an element from the set of $\underline{w}_{c(p)}$ to $\overline{w}_{c(p)}-z$ with z interval steps and *end* equals *start* $+\, z$. For example, a discrete time interval of 10 min and a 1-h customer time window from 1:00 until 2:00 results in six possible stopover time windows {1:00–1:10, 1:10–1:20, 1:20–1:30, 1:30–1:40, 1:40–1:50, 1:50–2:00}. The drives are set identically as in the case of the MPL mode. In order for a customer to be served during an AHD stopover, the stopover must occur at the customer's location and fit within the customer's time window.

Table 3 provides examples of stopover calculations. To keep the example simple, no travel times are involved. Therefore, the arrival time is equal to the departure time for all generated σ. An example with 1 h of travel time between two points is σ(MPL, p_1, p_2, 3:00) = 2:00.

TABLE 3 FPL/MPL/AHD example with only one location.

	FPL-location p	**MPL-location** p	**AHD-location** p
Available from	$\underline{w} = 1{:}00$	$\underline{w} = 1{:}00$	$\underline{w}_{c(p)} = 1{:}00$
Available until	$\overline{w} = 4{:}00$	$\overline{w} = 4{:}00$	$\overline{w}_{c(p)} = 2{:}00$
Discretization	-	$z = 1$ h	$z = 10$ min
Number of stopovers	1	6	6
Generated stopovers	(FPL, p, 1:00, 4:00)	(MPL, p, 1:00, 2:00)	(AHD, p, 1:00, 1:10)
		(MPL, p, 1:00, 3:00)	(AHD, p, 1:10, 1:20)
		(MPL, p, 1:00, 4:00)	(AHD, p, 1:20, 1:30)
		(MPL, p, 2:00, 3:00)	(AHD, p, 1:30, 1:40)
		(MPL, p, 2:00, 4:00)	(AHD, p, 1:40, 1:50)
		(MPL, p, 3:00, 4:00)	(AHD, p, 1:50, 2:00)
Number of drives	2	4	7
Generated drives	(FPL, γ, p, 1:00)	(MPL, γ, p, 1:00)	(AHD, γ, p, 1:00)
	(FPL, p, γ, 4:00)	(MPL, p, p, 2:00)	(AHD, p, p, 1:10)
		(MPL, p, p, 3:00)	(AHD, p, p, 1:20)
		(MPL, p, γ, 4:00)	(AHD, p, p, 1:30)
			(AHD, p, p, 1:40)
			(AHD, p, p, 1:50)
			(AHD, p, γ, 2:00)
Number of σ	2	4	7
Derived σ	(FPL, γ, p, 1:00) = 1:00	(MPL, γ, p, 1:00) = 1:00	(AHD, γ, p, 1:00) = 1:00
	(FPL, p, γ, 4:00) = 4:00	(MPL, p, p, 2:00) = 2:00	(AHD, p, p, 1:10) = 1:10
		(MPL, p, p, 3:00) = 3:00	(AHD, p, p, 1:20) = 1:20
		(MPL, p, γ, 4:00) = 4:00	(AHD, p, p, 1:30) = 1:30
			(AHD, p, p, 1:40) = 1:40
			(AHD, p, p, 1:50) = 1:50
			(AHD, p, γ, 2:00) = 2:00

The predefined stopovers and drives are essential parts of the presented model. The number of stopovers and drives, along with the available lockers, are decisive for the computational complexity of the problem. To reduce the problem size without losing optimality, we apply preprocessing as presented by Schwerdfeger and Boysen [18]. This includes reducing stopovers when they are no option for the current customers as well as eliminating non-essential drives. For instance, in our example in Table 3, we could remove AHD stopovers and adjust the drives accordingly, as we only need to address each customer once. Additionally, in the given example with only one MPL location and no possibility to move to any other location, we could remove all MPL stopovers except the stopover (MPL, p, 1:00, 4:00).

5 | COMPUTATIONAL STUDY

We investigate the performance of the individual delivery services and the service combinations through a computational study. First, the experimental setup is described. This is followed by a detailed presentation and discussion of the experimental results, differentiated according to instance, locker, and service characteristics.

5.1 | Experimental setup

We consider 100, 200, and 400 customers distributed in an area of 10 km in length and width. Customer locations stem from the VRPTW instances by Solomon [21] and Gehring and Homberger [8]. They are tightly clustered in C1, less tightly clustered in C2, randomly distributed in R1, and a mixture of R1 and C1 locations is chosen in RC1. The distribution of 200 customer locations for these instance types are shown in the appendix, see Figure A1.

We define two customer types with different preferences: **restrictive** and **flexible** customers. Based on the above instances, these are randomly assigned with equal probability. Restrictive customers have a restrictive willingness for pickup efforts—that is, only accept closer stopovers—and have shorter pickup time windows. Flexible customers are willing to travel a bit further to their pickup location in exchange for more flexibility in terms of a longer pickup time window. To clearly distinguish between these types of customers, we have made the following assumptions: restrictive customers are willing to travel a maximum of 0.5 km and are offered pickup time windows of 1 h length. Flexible customers have 4 h to pick up their items and are willing to travel up to 2.5 km to the pickup location. The restrictive customers have a very limited pickup range, whereas the flexible customers demand a considerable amount of time for pickup. These two customers with their own unique characteristics allow us to observe how the different services behave under certain circumstances.

The temporal distribution of time windows is based on the real-world data by Köhler and Haferkamp [15] for unequal demand in metropolitan areas. The available time windows span 12 h (10:00–22:00). Since Köhler and Haferkamp considered only 2-h time windows, we distribute/aggregate the demand probabilities equally for 1-h time windows and 4-h time windows. The combined probabilities for customer type and time window preferences are shown in Figure 3. As an example, the probability for a time window from 10:00 to 12:00 according to Köhler and Haferkamp is 25%. Half of these contribute to flexible 10–14 customers and the remaining 12.5% are divided equally between 10–11 and 11–12 restrictive customers (6.25% and 6.25%). Based on these distributions, 10 instances were randomly generated for each of the four instance types in the time period from 10:00 to 22:00.

The above combinations of four instance types and ten customer scenarios are examined for each delivery service, namely FPL, MPL, AHD, and the combinations FPL&MPL, AHD&FPL, and AHD&MPL. The number of available lockers is varied and set to four, eight, or ten in each service. The total capacity of the delivery resources corresponds to the number of customers and is distributed equally among the locker-based services. Given a total capacity of 100/200/400 compartments, this results in four big lockers with 25/50/100 compartments, eight medium lockers with 13/25/50 compartments, and ten small lockers with 10/20/40 compartments, respectively. For the combined services, resources are split 50/50, that is, two fixed and two mobile lockers, four fixed and four mobile lockers and so forth.

We assume that customer locations can serve as potential stopover locations for each service. Inherently, AHD stopovers are permitted at every customer location. For FPL and MPL, we use a k-medoid clustering algorithm to identify smaller sets of locker locations. To determine appropriate FPL locations, customer locations were clustered for each instance type separately (C1, C2, R1, RC1) according to the number of available lockers (2, 4, 5, 8, 10). As a result, cluster centers (here: locker locations) have been selected such that the overall customer travel distance is minimal for each instance type and number of available lockers. To identify reasonable locations for MPL, 50 clusters were generated. Thus, it is possible to have a stopover at 50%/25%/12.5% of the customer locations, and each stopover will cover an average of 2 km^2.

The duration of a stopover varies according to the delivery service. Since FPLs have a fixed location, they offer pickup services across the whole planning horizon (12 h). MPLs can stay at a stopover for 1 to 12 h. For AHD, the time required for stopovers is set to 12 min as various service times ranging from 5 to 20 min can be found in the literature [1, 22]. The travel times for repositioning for AHD and MPL services are based on a travel speed of 30 km per hour and are discretized in 12-min intervals. The discretization is based on experiments conducted with 200 customers to achieve an acceptable calculation time of below 1 h, see Table A1 in the appendix for details. For a customer to be served by MPL, the locker must cover the entire pickup time window, that is, a minimum stopover of 1 h is required. Hence, if a MPL changes its location, it is not available for service in the corresponding 1-h time slot. Therefore, observed times for repositioning may be higher than the actual times, especially for the MPL service.

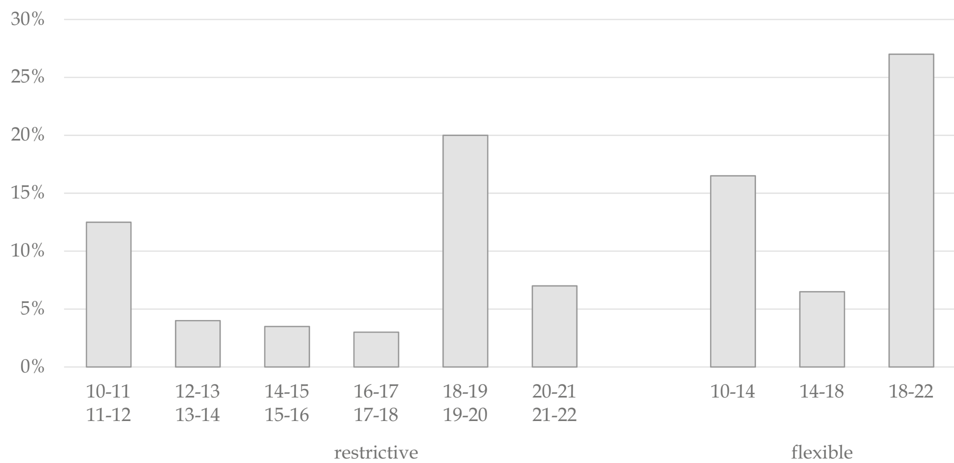

FIGURE 3 Probabilities for customer type and time window preferences.

All experiments were performed on a computational cluster with Xeon-G 6226R processors at 2.9 GHz, using up to five cores and 384 GB memory. For 68 of 4320 calculations, no solutions could be found within the maximum runtime of 1 h, for details see Table A2; these 68 cases were excluded from the reported results.

5.2 | Results and discussion

With our computational results, we focus on managerial insights including service quality and efficiency of the individual delivery services, in particular the impact of restrictive and flexible customers. The *number of served customers* (objective function) will be the main indicator for efficiency. In addition, efforts for repositioning of the lockers (repositioning time), the utilization of the locker capacities, as well as the efforts required for pickup (distances) and acceptance probabilities for different time windows will be examined. First, Section 5.2.1 provides an overview of the results by generally comparing the performance of the investigated services with 100, 200, and 400 customers. This is followed by a more detailed discussion of the impact of the instance type characteristics (Section 5.2.2), the utilized lockers (Section 5.2.3), and the service characteristics for the different customer types (Section 5.2.4) with 200 customers. Finally, we briefly discuss a more conservative scenario in Section 5.2.5.

5.2.1 | Overview

To assess the potential of each of the separate services and service combinations, Figure 4 presents the proportion of served customers aggregated across all instances and locker variations. There are clear differences despite the same number of lockers being used. For example, FPL can handle only 56% of customers on average, whereas the combination of AHD&MPL can achieve 81%. Among single services, AHD performs best with 71% accepted customers, followed by MPL with 66%, and FPL with 56% served customers. FPL&MPL is exactly in the middle of the separate counterparts. Since the lockers in MPL can also remain in one place all day and have more locations to choose from, the combination with FPL leads to a "downgrade" of certain lockers. In contrast, AHD&FPL and AHD&MPL can handle more customers than the separate services. Here again, the combination with MPL is superior to the FPL combination. **In sum, we see that FPL and MPL services are inferior to AHD in terms of customer acceptance. The combination of different services leads to a higher number of customers to be accepted.**

Figure 5 compares how the services perform for 100, 200, or 400 customers. For each service, the proportion of customers served is highest for 100 customers and lowest for 400 customers. The differences are rather small for the FPL and MPL services. FPL can serve from 54% of the 400 customers to 57% of the 100 customers, whereas MPL achieves between 60% and 74%. In contrast, AHD&FPL and AHD&MPL show a significant performance difference with 63% and 90% as well as 66% and 95%. However, the largest spread is seen for AHD, where 95% of the 100 customers can be served and only 45% of the 400 customers. **With AHDs, a higher number of customers is more difficult to serve because, unlike with parcel lockers, there is no possibility of serving several customers at the same time.**

When there are 100 customers, in many cases all customers are served. When there are 400 customers, for 38 instances no solutions could be found. While 33 of these instances involve AHDs, it can be observed that the upper bound of maximum number of customers served for all AHD instances with 400 customers is 48%. For these reasons, in the following, we will focus on the details of instances with 200 customers.

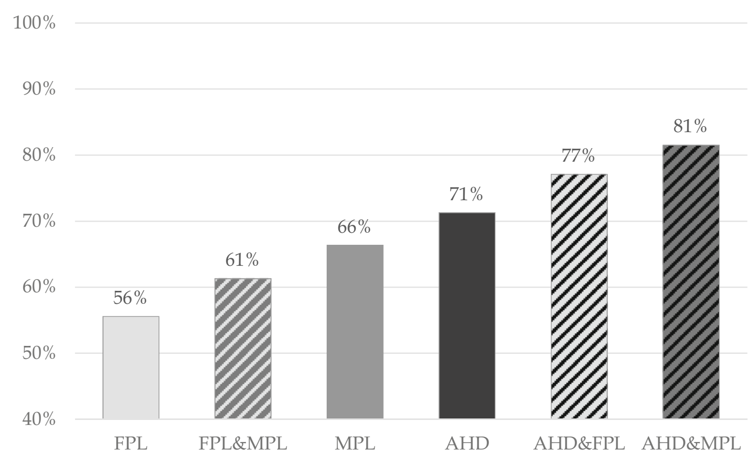

FIGURE 4 Accepted customers for different services.

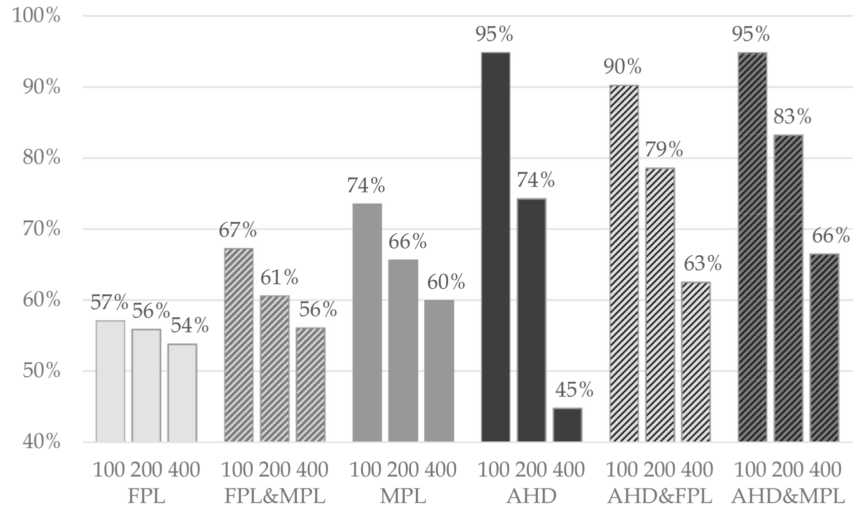

FIGURE 5 Accepted customers for different services and number of customers.

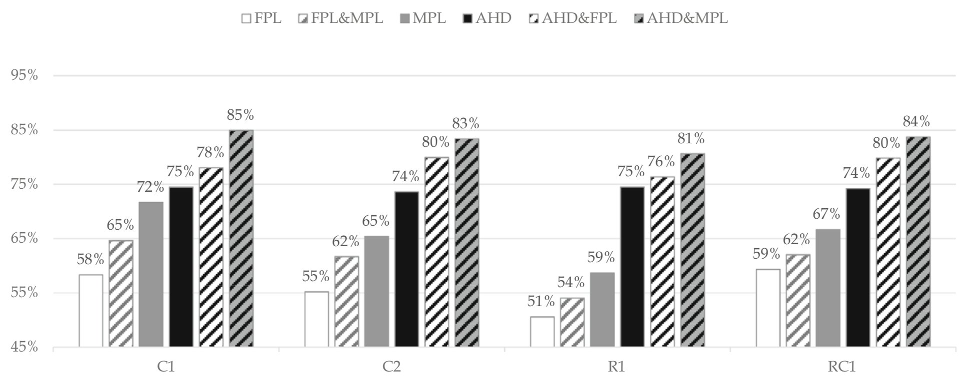

FIGURE 6 Accepted customers for different services and instance types.

5.2.2 | Instance characteristics

We now assess the results of the instance types for 200 customers in detail. Figure 6 compares the proportion of customers served for the different services across the four different instance types. Generally, customer acceptance follows the same ranking across all instances as observed before (see Figure 4), with FPL showing the smallest acceptance rates (51%–59%) and AHD&MPL showing the highest acceptance rates (81%–85%). However, FPL and MPL work much better for clustered instance types than for random customer locations, as represented by R1. AHD-based variants can adapt best to varying spatial characteristics and accommodate at least 74% of customers in every instance type. **Overall, the impact of spatial instance characteristics can be seen clearly for MPL: the more clustered the customer locations, the higher the potential of customer acceptance. Combinations of AHD and MPL can adapt to any of these characteristics.**

A detailed look into why customers could not be accepted is provided by Figure 7 for separate services and Figure 8 for service combinations. "Restrictive" and "flexible" represent the type of accepted customers, while "time/capacity" and "distance" represent the reasons for rejection. The rejection due to time window or capacity is based on resource constraints, while the other category highlights the customers that have been impossible to be reached due to their limited willingness of pickup efforts.

For FPL, we see a large chunk of rejections related to infeasible pickup distances, while there are barely rejections due to capacity issues. Across all instance types, the unserved customers are therefore predetermined by their pickup distances. The large majority of accepted customers are flexible customers. For both FPL and MPL, the rejected customers are determined by the customer's pickup distance. A higher number of accepted customers arises from the more flexible MPLs. No differences are apparent in AHD, where rejections only happen due to time or capacity issues, but not due to limited pickup distances.

As can be seen in Figure 8, FPL&MPL reduces the number of customers that have to be rejected by FPL due to insufficient distance. **Adding the AHD option to FPL or MPL helps transforming customers rejected due to pickup distance into accepted customers; again, only time/capacity-based rejections occur for AHD&FPL and AHD&MPL with almost no variations across the instance types.**

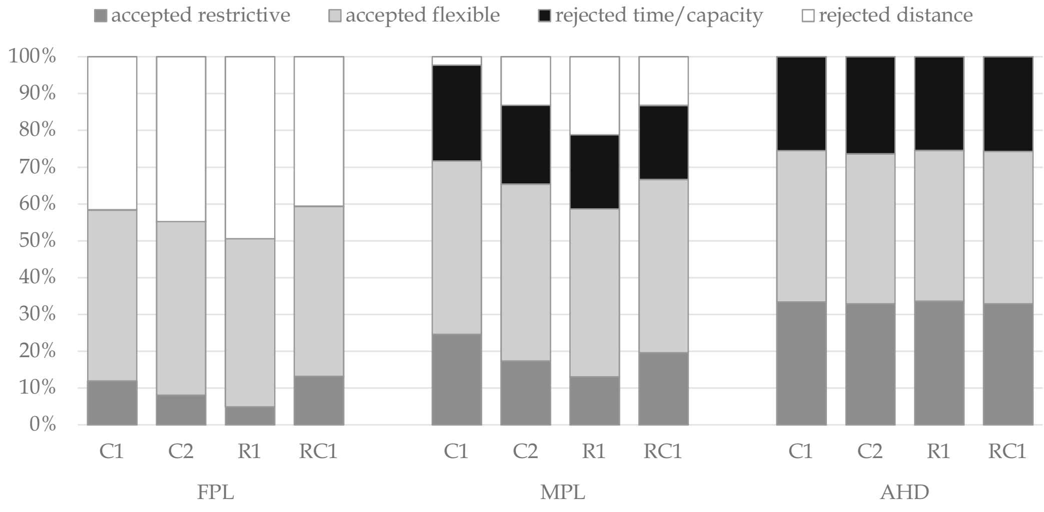

FIGURE 7 Types of accepted/rejected customers for single services/instance types.

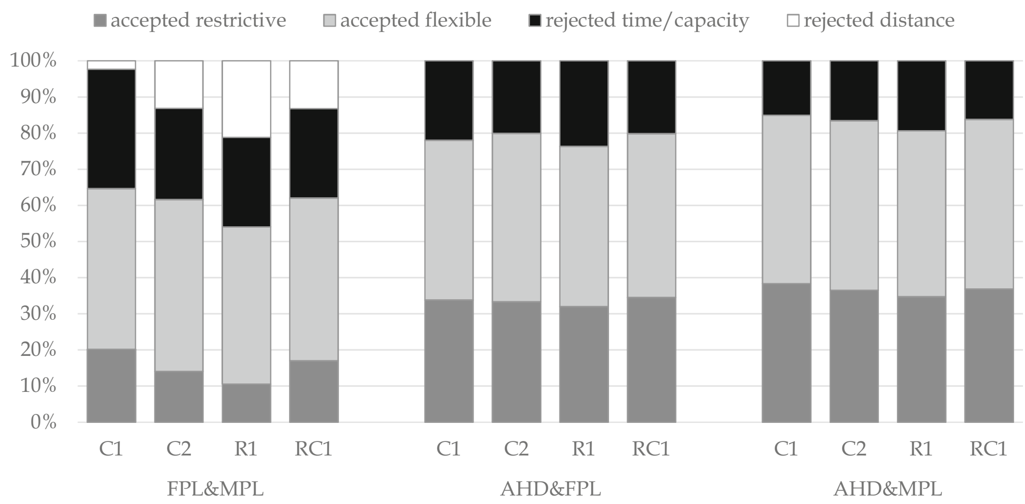

FIGURE 8 Types of accepted/rejected customers for combined services/instance types.

5.2.3 | Locker characteristics

We now investigate the impact of different numbers of lockers and their compartments for 200 customers. To this end, we consider 4 big lockers with 50 compartments, 8 medium lockers with 25 compartments, and 10 small lockers with 20 compartments, as described in Section 5.1. First, we show how this changes the number of served customers. Furthermore, we investigate how operational efficiency varies in terms of repositioning times of MPL and AHD as well as utilization of FPL, MPL, AHD, and their combinations.

Customer acceptance. Figure 9 shows the proportion of accepted customers for the separate and combined services with four big, eight medium, and ten small lockers, respectively. Overall, despite the total capacity remaining the same, we see an increasing yet saturating trend in all cases: More and smaller lockers allow for finer spatial dispersion of logistics resources and can hence meet customer demand better. While a significant proportion of flexible customers can already be served with four big lockers, regardless of the actual service, eight medium-sized lockers allow customer acceptance of over 90% for services combined with AHD. **Restrictive customers benefit most from additional lockers.**

As discussed before, combining services can increase the acceptance of restrictive customers significantly. Figure 10 shows how restrictive and flexible customers distribute across the individual services of combined services with varying locker sizes. Generally, being the most flexible service, AHD has the largest chunk of restrictive customers for AHD&FPL and AHD&MPL. For FPL&MPL, the more flexible service MPL has the larger chunk of restrictive customers. FPL and AHD seem to be particularly good at exploiting their individual advantages. **Since MPL is capable of integrating restrictive customers when necessary and AHD is able to focus especially on remote customers, these two services complement each other particularly well.**

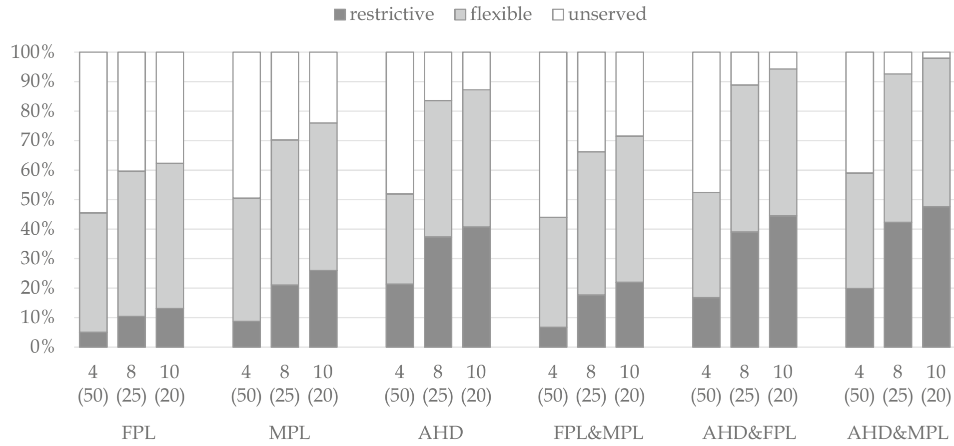

FIGURE 9 Customer types for different services and number of lockers (compartments).

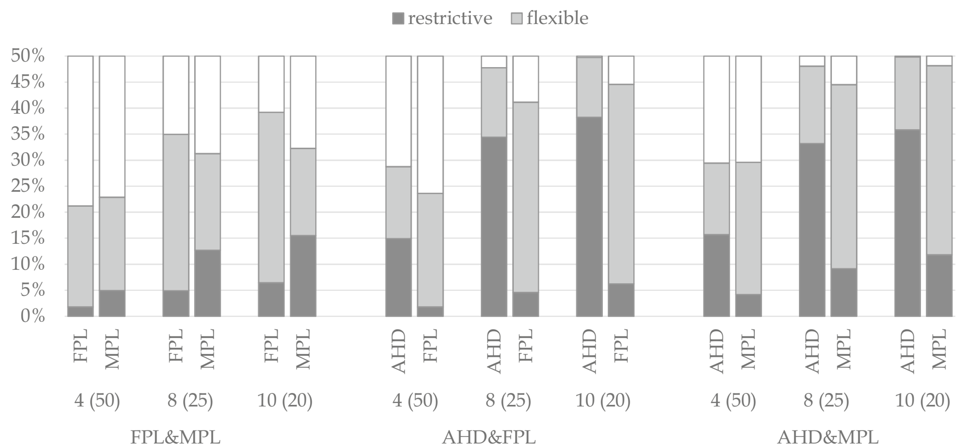

FIGURE 10 Customer types for combined services and number of lockers (compartments).

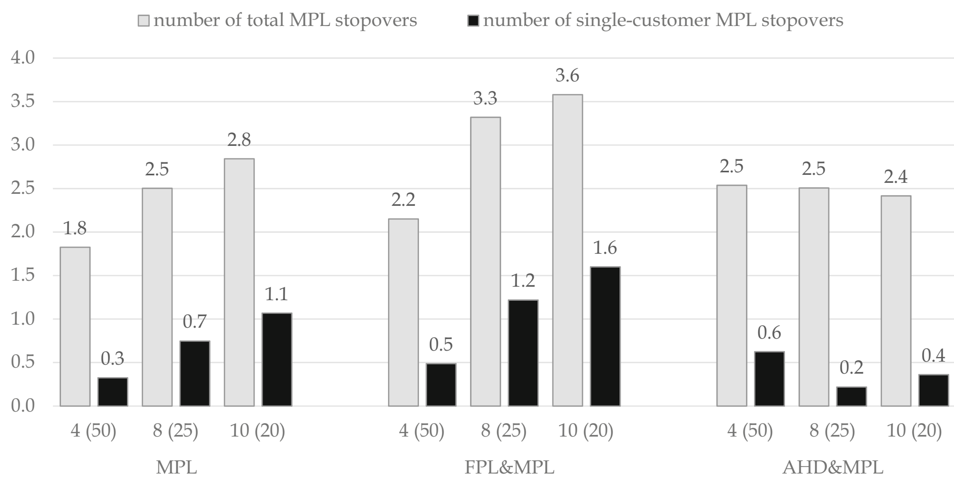

FIGURE 11 Number of MPL stopovers per locker, for different services and number of lockers (compartments).

With more lockers (and fewer compartments) at hand, MPL can adjust more flexibly to customer locations. Hence, they reposition more often, which is reported in Figure 11 showing how often MPL stop in total and how often they stop for only one customer. Both the number of total stopovers per locker and the number of single-customer stopovers per locker increase as the number of available lockers increases for separate MPL and when combined with FPL. The latter result in the highest number of single-customer stopovers. For AHD&MPL, with increasing number of lockers, both the total number of MPL stopovers and single-customer stopovers remain quite low and rather stable, indicating a reasonable allocation of customers between AHD and MPL.

Impact on traffic. Table 4 shows the percentage of the operating time one locker spends with repositioning relative to the total operating time (FPLs do not move at all). MPLs reposition 6.9%–15.4% of the total operating time. This increases as their number increases and helps accessing more remote customers. AHD drive the most with about 55% of the operational time being travel time. For FPL&MPL, repositioning times for MPLs increase up to 21.5%. AHD&MPL keep the MPL repositioning times around 12.5% of the total operating time. For AHD, the travel time remains similar, but in the combined services the travel time increases with a higher number of lockers. **In summary, MPL repositioning times are significantly lower compared to AHD. For AHD&MPL, differences become more pronounced with a higher number of lockers, the repositioning time increases for AHD and decreases for MPL.**

Table 5 shows the results from an absolute perspective, that is, it reports how many hours all lockers are actually in transit, based on the time-discrete implementation. Using ten lockers, MPLs are on the road for 18 h in total and AHDs are creating 67 h of travel time. It can be observed that the repositioning time increases with an increasing number of lockers. **AHD combinations cause significantly less total repositioning time than separate AHD. The combination of AHD with MPL not only serves more customers, but also reduces repositioning time up to 39%.**

TABLE 4 Repositioning times per locker, for different services and lockers.

Lockers number (compartments)	FPL	MPL	AHD	FPL&MPL		AHD&FPL		AHD&MPL	
				FPL	MPL	AHD	FPL	AHD	MPL
4 (50)	0%	6.9%	54.5%	0%	9.6%	51.4%	0%	50.9%	12.8%
8 (25)	0%	12.5%	56.3%	0%	19.3%	55.3%	0%	54.5%	12.6%
10 (20)	0%	15.4%	55.9%	0%	21.5%	56.9%	0%	57.0%	11.8%

TABLE 5 Total repositioning time comparison, for different services and lockers.

Lockers number (compartments)	FPL	MPL	AHD	FPL&MPL	AHD&FPL	AHD&MPL
4 (50)	0 h	3 h	26 h	2 h	12 h	15 h
8 (25)	0 h	12 h	54 h	9 h	27 h	32 h
10 (20)	0 h	18 h	67 h	13 h	34 h	41 h

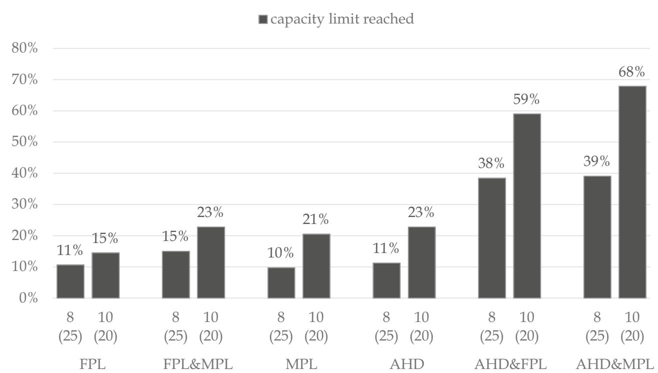

FIGURE 12 Percentage of lockers at capacity limit, for different services and number of lockers (compartments).

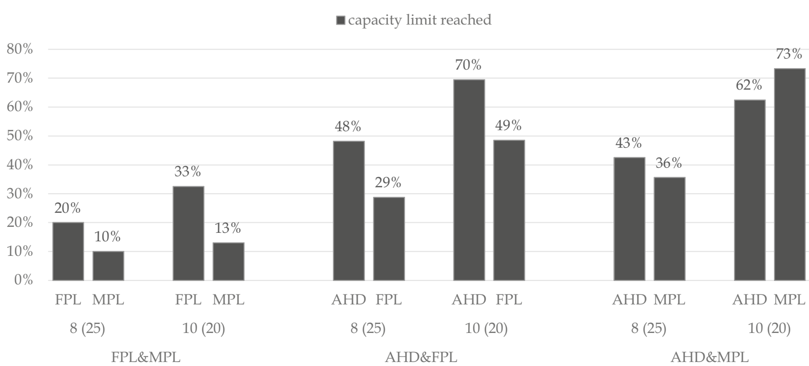

FIGURE 13 Percentage of lockers at capacity limit, for combined services and number of lockers (compartments).

Locker utilization. From an economic perspective, it is interesting how well the available resources—different number of lockers with different capacities, that is, number of compartments—are used. As seen before, the total capacity utilization increases with combined services, as an increasing number of customers served aligns with how the logistics capacity is used overall. Now we narrow this down and investigate in which cases capacity limits are the reason for rejection. Figure 12 shows the percentage of lockers that have reached the capacity limit for all services. With four lockers and a capacity of 50 compartments per locker, there is never a capacity problem, which is why this has been omitted in the figure. With an increasing number of lockers and smaller capacity per locker, for AHD combinations, lockers reach capacity significantly more often than all other services. In particular, while for most services there are between 10% to 23% of lockers at capacity, this increases to 38% or 68% for the AHD combinations. Again, this aligns with the high ratio of customers served.

Figure 13 presents the proportion of lockers at their capacity limit for the combined services. Generally, the more flexible the service and the higher the number of lockers, the higher the risk of limited capacity. For FPL&MPL, FPLs are more likely to be fully utilized, and this increases with an increasing number of (smaller) lockers. For AHD&FPL, the use of both modes increases with the number of lockers. FPLs are less often at the limit than AHDs, with a gap of about 20%. For AHD&MPL, there is no clear pattern. Limited AHD capacities are more often at their capacity limit when eight medium-sized lockers are in operation, but this shifts to MPLs when operating ten small lockers. Therefore, with ten lockers, more MPLs reach the capacity limit than AHDs. **Overall for AHD&MPL, the capacity utilization seems to be the most evenly distributed,** suggesting that there is further potential to serve additional customers, even though the majority of existing customers have already been served.

5.2.4 | Service characteristics

In the following, we analyze the services from the customer's perspective. This involves the impact of the pickup distances, and the probability of acceptance of a specific customer.

Figure 14 shows the percentage of the maximum pickup distance, the average restrictive or flexible customer might expect, across the different delivery services. The average customer has to travel about half the maximum pickup distance unless AHD is involved (which does not require traveling by definition). In favor of their preferences, the restrictive customers need to travel less than the flexible customers. The restrictive customers consume their maximum pickup distance by 45%, whereas the flexible customers have to travel up to 57% on average. **For the AHD combinations, on average, customers benefit from shorter distances compared to the other services. Matching their preferences, the restrictive customers benefit to a greater extent, as they are supplied mainly via AHD.**

Some customers cannot be served by FPL or MPL at all due to their restricted willingness to travel. Figure 15 shows the percentage of restrictive and flexible customers that could not be served by any of the available FPL and MPL locations due to pickup restrictions. The number of customers that can be served varies with the number of FPL locations, whereas the available MPL locations remain the same in each case.

The limited pickup range of the restrictive customers is a clear disadvantage, especially for the FPL service. Overall, FPL is not able to serve 81% of restrictive customers individually and 91% when combined with MPL or AHD, respectively. Only 8% and 30% of flexible customers are affected. Based on the available MPL locations, none of the flexible customers and 25% of the restrictive customers cannot be served due to their pickup distance. A small number of FPLs cannot be positioned well enough and therefore leads to significantly lower customer acceptance rates. The possibility of repositioning through MPL helps alleviating that.

We now consider the acceptance probabilities of customer types by time window for separate services (Figure 16). Note that the 1-h time windows belong to restrictive customers and the 4-h time windows belong to flexible customers. Results for the combined services can be found in the appendix, see Figure A2. Overall, restrictive customers have a probability of 56%

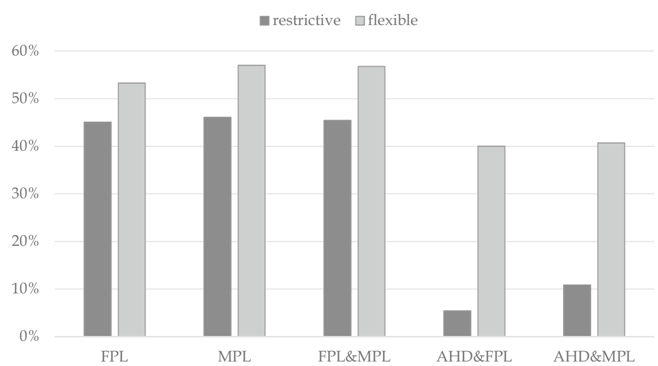

FIGURE 14 Average pickup distance for different services.

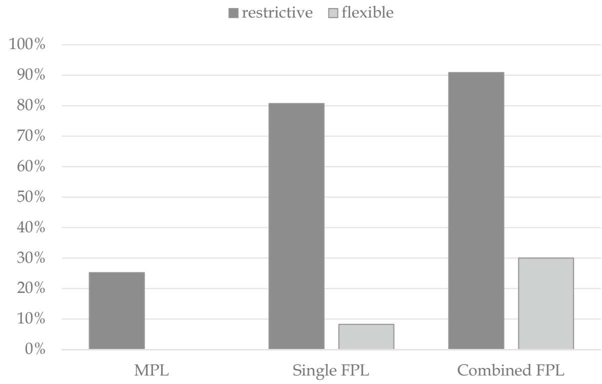

FIGURE 15 Proportion of customers who cannot be served per service/service combination.

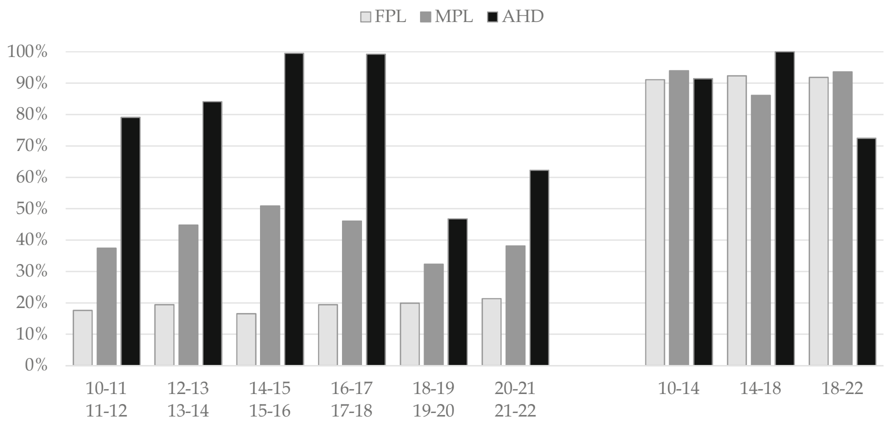

FIGURE 16 Acceptance probability of customers for single services by time window.

of being accepted across all constellations and services, whereas flexible customers can expect an acceptance rate of around 91%. For restrictive customers (left side), we see for FPL that it is very balanced, always just below 20%, regardless of the time window. For MPL and AHD, the acceptance probability depends on the number of customers in the respective time window. However, this is much more pronounced for AHDs with up to 99% acceptance probability than for MPLs with up to 51%.

Second, we take a look at the flexible customers on the right side of the Figure 16. In the case of FPLs, the time windows again show no influence, and the probability of acceptance is about 92% for each of them. With AHD, this increases up to 100% in the time window 14–18. For MPLs, however, no obvious trend can be identified. In each of the time windows 10–14 and 18–22, 94% of the customers can be accepted, although the customer demand is clearly different. In time window 14–18, the probability of acceptance is the lowest, although demand has also been the lowest.

Third, if we compare the restrictive customers with the flexible customers, we see a clear difference between the customer types, with acceptance probabilities of up to 20% and 92% if served by FPLs. This is similar but less significant in the case of MPLs. In contrast, for AHDs this trend is barely discernible, but the flexible customers are also favored. For example, customer demand in the 20–21, 21–22, and 14–18 time windows is roughly identical, yet the flexible 14–18 customers are more likely to be served. This could be because there is more time in the longer flexible time window or because there are many flexible customers in the 18–22 time window and they are preferred over the restrictive customers.

Finally, we examine how the acceptance probabilities of the average restrictive and flexible customer are affected by combined services. For this purpose, Figure 17 shows the three service combinations and in each case the corresponding change in the acceptance rate of each customer type based on the underlying separate service type. Relative to FPLs, FPL&MPL can serve 6% more restrictive customers, whereas MPLs lose a small number of both restrictive and flexible customers. Note that the acceptance of flexible customers even decreases slightly in comparison to separate FPLs.

In summary, in most cases, both customer types benefit from the AHD combinations. Only for AHD&FPL, the served flexible customers decrease by 1% in comparison to separate FPLs. By combining AHDs with FPLs or MPLs, it is possible to serve 4% or 6% more flexible customers without losing restrictive customers. In contrast, the combination of FPLs or MPLs with AHDs particularly benefits restrictive customers, whose acceptance probability increases by 24% or 18%, respectively. Both customer types benefit most from the combination with MPL.

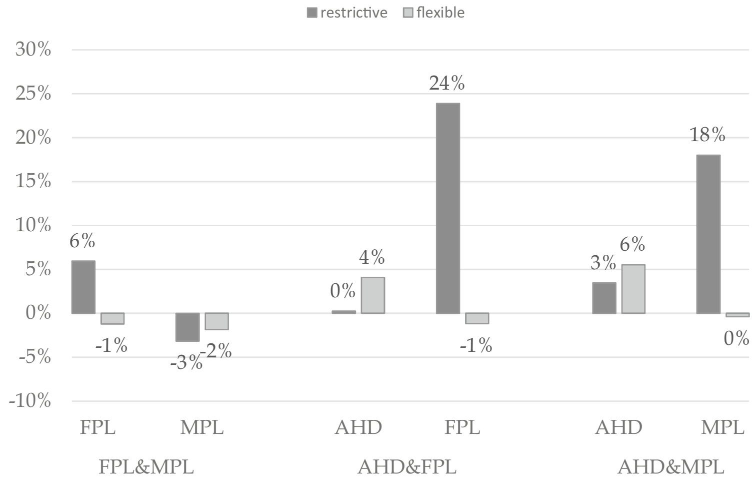

FIGURE 17 Comparison of served customer types, through combined services instead of single services.

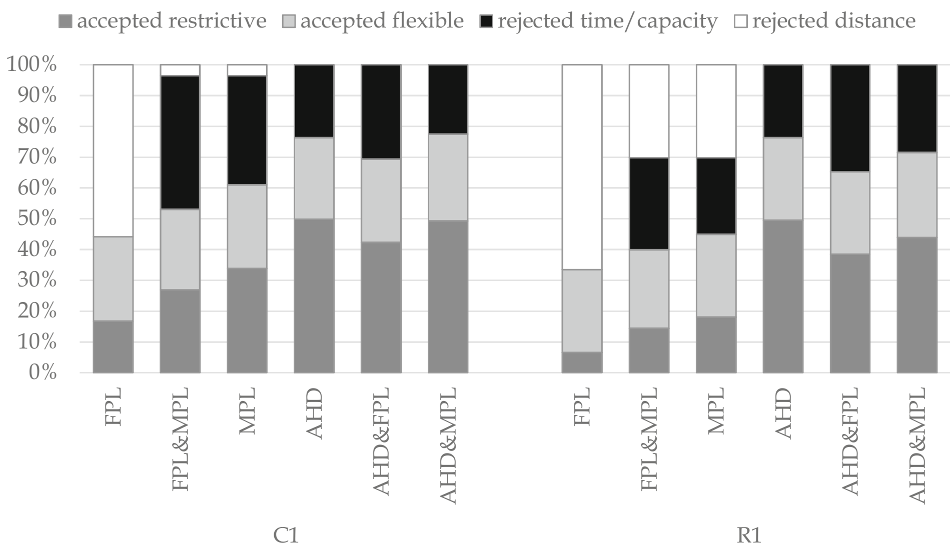

FIGURE 18 Types of accepted/rejected customers for 200 customers with 70% restrictive and 30% flexible customers.

5.2.5 | Conservative scenario

In practice, it is quite unlikely that the customer types are equally distributed, as it was assumed in our previous experiments to better highlight differences between customer types. Since we do not have real data on customer behavior, the following analysis aims to provide additional insights using a more "conservative" scenario. For this purpose, we consider a distribution of 70% restrictive customers and 30% flexible customers for the example of C1 and R1 instances with 200 customers.

As Figure 18 shows, the 30% flexible customers can be served almost completely by all services or service combinations. However, due to the high proportion of restrictive customers, the gap between instances with different spatial characteristics increases for both FPL and MPL services. This is particularly evident for MPLs, where 30% of the customers in R1 instances cannot be reached due to the limited pickup distances. For C1 instances, AHD&MPL is on par with single AHDs in terms of acceptance rates, but for R1 instances, it is 4.8 percentage points below AHD. Furthermore, the AHD combinations can no longer achieve higher acceptance rates than single AHD, which highlights that a minimum number of more flexible customers is required to make the combinations advantageous regarding the number of accepted customers. Nevertheless, the effects explained in the previous sections, such as less traffic or undesired service, are still in place. Thus, even in the more conservative scenario, the AHD&MPL combination gives 66% of the flexible customers the desired flexibility. Furthermore, in Figure A3, we depict the accepted customers for the conservative scenario with 100, 200, and 400 customers. The results are similar to the ones depicted in Figure 5, so not only the ratio of customer types is relevant for the efficiency of the combined services, but also the ratio of available lockers to the number of customers.

6 | CONCLUSION

We have presented the HLLP to evaluate different innovative delivery services for last-mile deliveries: FPLs, MPLs, AHDs, and their combinations. In the experiments, we have considered instance types that differ in spatial characteristics. Two distinctly different types of customers have been designed. Restrictive customers have a limited willingness to travel and shorter pickup time windows, while flexible customers are willing to travel further in exchange for more flexibility.

The results show that AHDs dominate FPLs and MPLs. However, combining delivery services can improve acceptance rates for both types of customers and produces significantly less traffic compared to a single AHD service. FPLs and MPLs serve many customers in a short period of time, and AHDs serve customers efficiently regardless of their location and willingness to travel. The AHD combinations achieve good results, but AHD&MPL is slightly better and seems to have more spare capacity for additional customers. The main weakness of a small number of FPLs is accessibility, hence they are mainly used by flexible customers. For MPLs, spatially clustered customers showed clear advantages, whereas spatial characteristics do not affect AHDs. From the customers' point of view, the acceptance probabilities result from the selected customer type with FPLs, from the selected time window with AHDs, and from a blend of both features with MPLs.

We see some directions for future research. In the literature, well advanced solution approaches for AHDs are available, but we used a discrete-time based MIP structure to solve it for the sake of simpler comparability. Continuous and metaheuristic approaches can help to increase the degree of realism and to find good solutions for larger problems. In addition, stochastic customer demand might be considered in order to evaluate how well the different services can adapt to uncertainties. Furthermore, considering multiple delivery locations and time windows for each customer as well as more diverse customer types would be of relevance. This includes sensitivity analyzes on varying willingness to travel and spatio-temporal flexibility. This could help gaining a deeper understanding of the relationship between customer preferences and service offerings. To provide strategic guidance to service providers, investment and operating costs should be considered and evaluated in relation to the level of customer service achieved.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX A

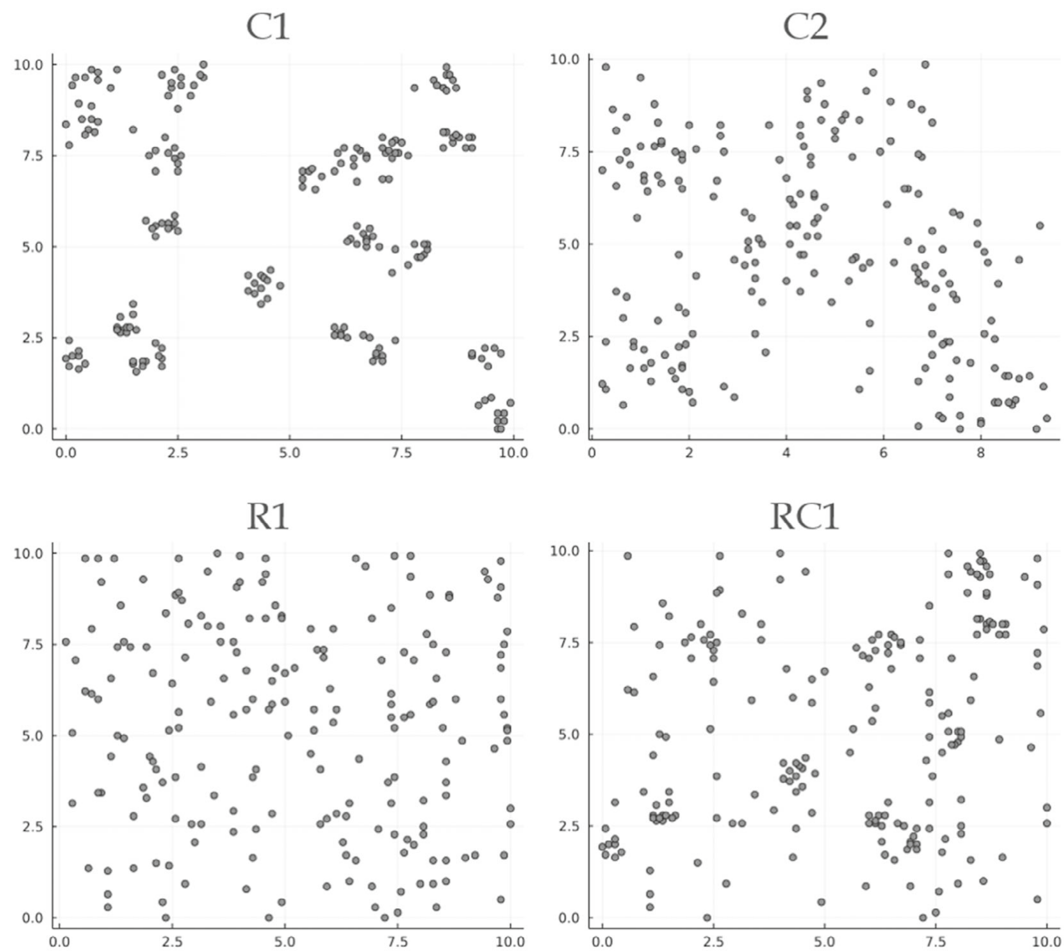

FIGURE A1 200 customer location distributions following Gehring and Homberger [8]

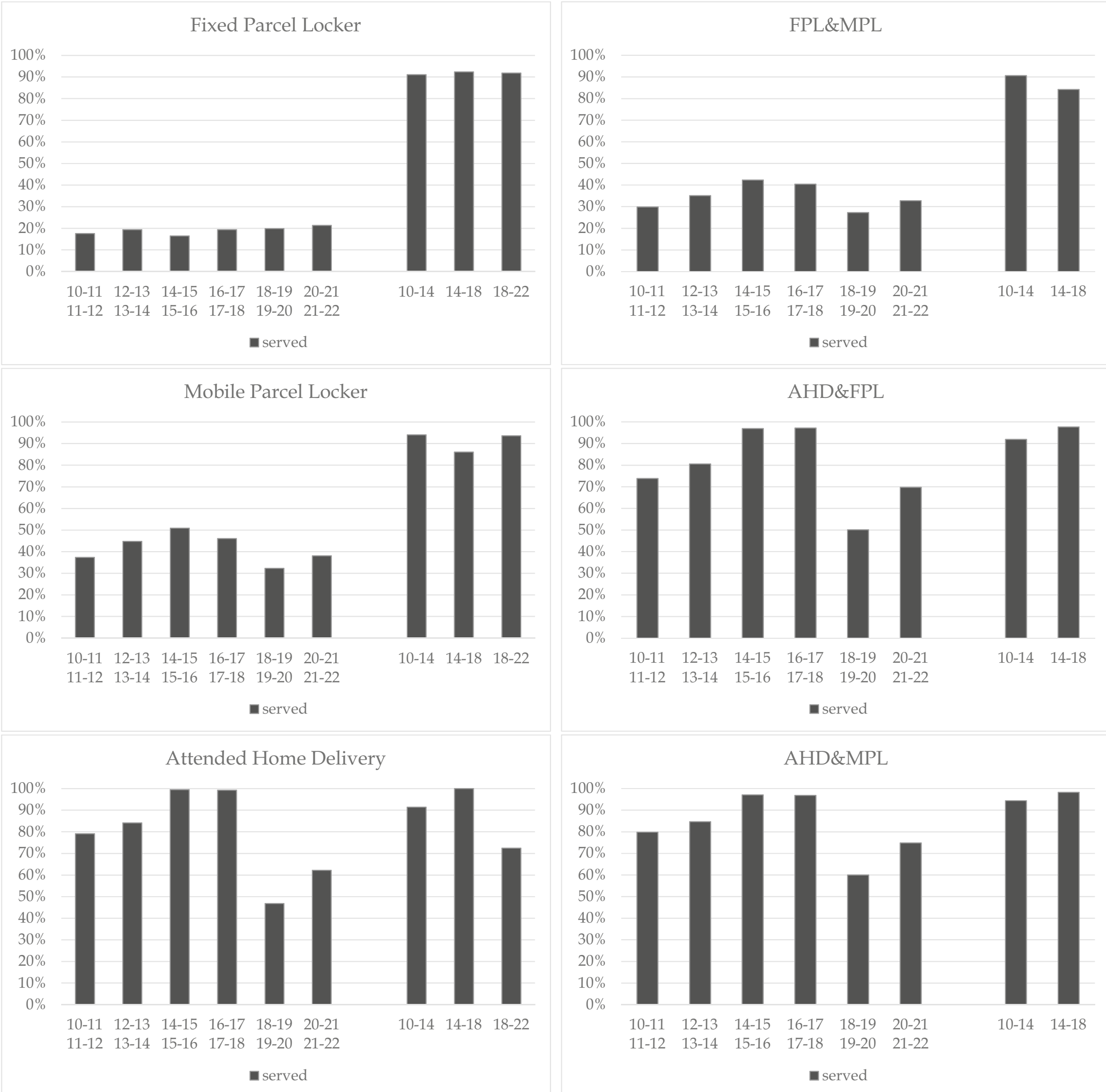

FIGURE A2 Acceptance probability of customers for single services by time window.

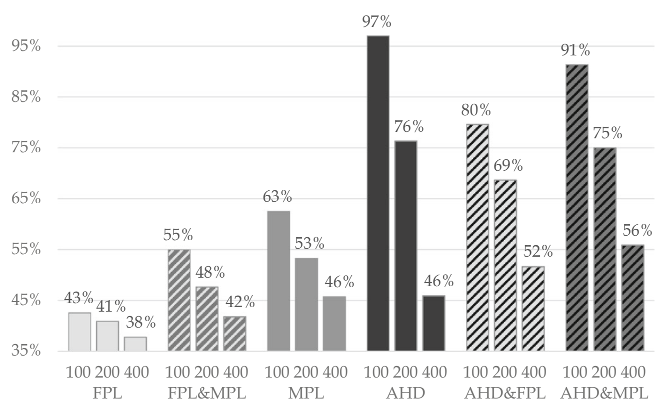

FIGURE A3 Accepted customers for different services and number of customers for 70% restrictive and 30% flexible customers.

TABLE A1 Average runtime for different discretization levels (200 customers, three C1 instances and 180 min time limit).

Discretization	15 min	12 min	10 min
AHD with 8 lockers	5 min	27 min	103 min
AHD with 10 lockers	9 min	41 min	169 min

TABLE A2 Average runtime and gap for each service (excluding instances with no solution).

Customers	Service	Runtime	Gap	Instances with no solution
100	FPL	0.1 s	0.00%	-
50% restrictive	FPL&MPL	9.5 s	0.00%	-
50% flexible	MPL	74.8 s	0.01%	-
	AHD	45.8 s	0.00%	-
	AHD&FPL	35.9 s	0.00%	-
	AHD&MPL	58.3 s	0.00%	-
200	FPL	0.2 s	0.00%	-
50% restrictive	FPL&MPL	12.5 s	0.00%	-
50% flexible	MPL	104.7 s	0.01%	-
	AHD	1613.1 s	2.62%	-
	AHD&FPL	920.8 s	0.19%	-
	AHD&MPL	1180.5 s	0.05%	1xC1
400	FPL	0.3 s	0.00%	-
50% restrictive	FPL&MPL	11.4 s	0.00%	-
50% flexible	MPL	95.2 s	0.00%	-
	AHD	2625.9 s	5.80%	10xC1, 6xC2, 9xR1, 8xRC1
	AHD&FPL	1716.0 s	1.15%	-
	AHD&MPL	1864.7 s	0.84%	1xC1, 3xC2, 1xRC1
100	FPL	0.2 s	0.00%	-
70% restrictive	FPL&MPL	7.8 s	0.00%	-
30% flexible	MPL	23.7 s	0.00%	-
	AHD	31.6 s	0.00%	-
	AHD&FPL	20.9 s	0.00%	-
	AHD&MPL	113.9 s	0.01%	-
200	FPL	0.1 s	0.00%	-
70% restrictive	FPL&MPL	7.4 s	0.00%	-
30% flexible	MPL	23.2 s	0.00%	-
	AHD	326.5 s	0.00%	-
	AHD&FPL	113.8 s	0.00%	-
	AHD&MPL	390.9 s	0.00%	-
400	FPL	0.2 s	0.00%	-
70% restrictive	FPL&MPL	9.5 s	0.00%	-
30% flexible	MPL	35.8 s	0.00%	-
	AHD	2141.5 s	4.13%	7xC1, 6xC2, 7xR1, 9xRC1
	AHD&FPL	431.6 s	0.03%	-
	AHD&MPL	924.7 s	0.15%	-