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 continuously being investigated to provide these deliveries efficiently and in a customer-friendly manner. A common practice is to use fixed parcel lockers to make deliveries independent from the presence of the customer as is the case in attended home deliveries. Fixed parcel lockers 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 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 parcel lockers at low costs.

In this paper, we propose a mixed-integer program to evaluate different innovative delivery services – fixed parcel lockers, mobile parcel lockers, attended home deliveries, and their combinations – 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 and possible combinations 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 12-17\% through the use of mobile parcel lockers while considering individual customer preferences.
1 Introduction

Last-mile delivery is the most challenging factor in terms of costs and planning when delivering goods to private customers (Joerss et al., 2016). 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 delivery failures and in further delivery attempts. Therefore, customers and logistics service providers are increasingly planning short delivery time windows to reduce the risk of failed deliveries and to enable customers to plan their daily schedules more flexibly (Hübner et al., 2016). While this reduces delivery failures, providers are restricted in their tour planning.

To avoid the high cost of deliveries and delivery failures, another common way of last-mile services is fixed parcel lockers (FPLs), which are filled by the logistics provider regularly, e.g. once every morning. Then, the customer can pick up the parcel at any time. The pickup time for the customer is flexible and the costs for logistics service providers are relatively low. 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. For the provider, detours and failed deliveries are minimized. A study by McKinsey showed that 70% of customers prefer low-cost delivery, but prefer home delivery to parcel locker if the costs are the same (Joerss et al., 2016).

A new and innovative service design is mobile parcel lockers (MPLs), which can change their location with or without a driver (Schwerdfeger and Boysen, 2022). In research and everyday life, this service has not received much attention yet. Some practical trials can be observed, e.g. by the postal service in Poland (InPost S.A., 2022) or a start-up in Berlin (Krisch, 2019). 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 attended home deliveries (AHDs), 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.

In this paper, we assume that customers have individual requirements regarding flexibility, and we try to accommodate these requirements as logistics service providers. 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 service variant, however, offer to combine these characteristics and provide an efficient service tailored to the individual customer. We compare last-mile deliveries with FPLs to a fleet of MPLs and to a fleet of AHD vehicles. We also investigate combinations of these services to accommodate individual customer preferences. 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.

Chapter 2 summarizes the relevant related literature. The problem is described in Chapter 3. Then, a mathematical model is presented and implementation details are discussed in Chapter 4. The design of the experiments and the results are described and discussed in Chapter 5. We conclude in Chapter 6.

2 Related Literature

A high-quality benchmark in logistics practice and research are last-mile delivery services via AHDs. Here, delivery time windows are scheduled to ensure the presence of customers during delivery and avoid failed delivery attempts. Dixit et al. (2019) and Kumar and Panneerselvam (2012) provide surveys on related problems involving the vehicle routing problem with time windows (VRPTW).

New trends in last-mile delivery are emerging, especially with FPLs and an increasing automation of the service (Behnke, 2019; Boysen et al., 2020). FPLs promise lower costs (Seghezzi et al., 2022), a positive impact on ecological sustainability (Eliyan et al., 2021), and the possibility to manage the constantly increasing transportation volume better (Zurel et al., 2018). A particularly convenient application for FPLs is the integration into a crowd shipping network (Gatta et al., 2018). Here, private individuals perform the transport of parcels during their daily commute, which is intended to reduce the traffic caused by last-mile deliveries (Chen et al., 2018). Other examples use FPLs as an alternative when AHD fails, e.g. (McLeod et al., 2006; Song et al., 2009); or to automate same-day deliveries (Ulmer and Streng, 2019); or as an intermediate storage facility in a two-tier distribution network (Enthoven et al., 2020; Redi et al., 2020; Pan et al., 2021). However, the decisive factors for the efficiency of FPLs are their position and capacity as determined by strategic planning (Deutsch and Golany, 2018; Faugère and Montreuil,
MPLs are a newer concept in which lockers are integrated into moving vehicles. This allows flexible positioning according to the actual demand (Schwerdfeger and Boysen, 2020; Wang et al., 2020a,b; Li et al., 2021). In addition, once these vehicles can be automated, large cost savings can be anticipated, see Li et al. (2021).

In addition to efficiency considerations, recently, individual customer preferences have been investigated in the context of last-mile deliveries. For instance, customers can now define several delivery options (Schwerdfeger and Boysen, 2020; Grabenschweiger et al., 2021; Mancini and Gansterer, 2021; Tilk et al., 2021) and even assign individual priorities to these options (Orenstein et al., 2019; Dumez et al., 2021). In this paper, we focus on the operational comparison of FPL, MPL, and AHD services, and all combinations including two services, taking into account individual customer preferences regarding time window flexibility and pickup efforts.

The most related papers are summarized in Table 1. All these papers deal with the implementation of parcel lockers in an operational problem and the integration of individual customer preferences. Which delivery services were included in each study is marked with [+] . It is also indicated whether the customers can specify one [1] or multiple [+] delivery locations. 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. pickup effort” column. Customers specify either no time window at all, one time window [1], or multiple time windows [+] . If the time window lengths are the same for all customers [no] or if they differ between the customers [yes] is 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.
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Orenstein et al. (2019) investigate FPLs in the context when customers can select multiple locations and assign priorities. Several papers address the integration of FPLs and AHDs. In the medical field, Veenstra et al. (2018) let the logistics service provider choose the mode of delivery, i.e. whether to deliver at home or by FPL, which implies opening costs. Enthoven et al. (2020) investigate a case where customers can choose between home delivery or FPL in a two-echelon system. Mancini and Gansterer (2021) add time windows and the third option that the customer would accept both deliveries via FPL and AHD. Grabenschweiger et al. (2021) allow always AHDs, and in addition, the customers can specify several FPL locations as alternatives. The next extension is introduced by Dumez et al. (2021) and Tilk et al. (2021), where multiple locations can be provided with time windows and individual priorities.

The concept of MPLs has been introduced by Schwerdfeger and Boysen (2020). They allow customers to specify multiple locations with a pickup radius and time windows. Based on the willingness to travel, suitable FPL and MPL locations are derived. They evaluate the required fleets to serve all customers with FPL and MPL, respectively, for different pickup distances. Wang et al. (2020a) consider single customer locations with a pickup radius in a pickup and delivery problem. The mobile locations are derived from the existing customers and a customer is served using either FPL or MPL. This work has been further extended to incorporate stochastic demand (Wang et al., 2020b).

Following up on Schwerdfeger and Boysen (2020), we introduce the Heterogeneous Locker Location Problem and apply this generic framework to all delivery services under consideration. To this end, we will adapt the mathematical model by changing the objective function and incorporating different delivery modes. With this, we will study the efficiency of the services with individual customer preferences comparing FPL, MPL, AHD services and their combinations.

3 Problem Description

In this work, we consider a variety of delivery services, which are primarily based on the concept of lockers. 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 in what period the pickup should occur. In this context, we try to find the appropriate “stopovers”,
which are defined by location and pickup time window, that maximize the number of customers served. In order to serve a customer at a specific stopover, the particular delivery service must respect the spatio-temporal preferences of the customer. A service vehicle can only serve as many customers as its capacity allows, and each customer can only be served by one vehicle.

The services we investigate are FPLs, MPLs, and AHDs. The latter are found in the majority of the literature and correspond to established industry practice. FPLs have exactly one location and one stopover where the customers can collect their delivery as soon as it is available. Contrasting FPLs, MPLs can change their location during the day and consider several possible pickup locations where stopovers can be scheduled. During a stopover, customers can collect their delivery at any time within a pickup time window. We, therefore, need to determine the routes of stopovers that serve as many customers as possible. AHDs consider as many locations as there are customers. AHD customers do not need to pick up their deliveries but receive them in their homes at a time specified by the logistics service provider within a given time window. We investigate the individual performance of FPL, MPL, and AHD as well as combinations of two service types. The challenge is to find the right combination of stopover locations and times to fulfill spatio-temporal restrictions efficiently.

Figure 1: Example for FPL, MPL, and AHD

![Figure 1](image-url)  

Figure 1 shows examples of problem realizations for FPL, MPL, and AHD with one single (fixed) locker and truck. The given four customers have a different maximum willingness of pickup effort (indicated by the pickup radius) and expect deliveries in different customer time windows (indicated by the time window). FPL has one dedicated location for pickup, which is not reachable by one customer due to the restricted pickup distance. The MPL tour has four potential stopovers, and two of them are chosen to reach all cus-
tomers and fulfill their time window constraints. AHD visits the given 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.

4 Heterogeneous Locker Location Problem

The problem described in Chapter 3 can be formalized as a Mixed Integer Program (MIP). In the following, we provide a detailed explanation of the MIP and then address its parameterization for different locker types. We use the model to optimize deliveries based on FPLs, MPLs, and AHDs, as well as their combinations FPL&MPL, AHD&FPL, and AHD&MPL. The model has been adapted from the time discretization-based mobile locker location problem by Schwerdländer and Boysen (2020). The modifications involve the objective function, as well as relevant constraints and the consideration of multiple heterogeneous locker types.

4.1 General Model

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, \( \gamma \) represents another location at which each route of a locker must start and end.

The spatial and temporal assignment of the locations is realized by the stopovers. The set \( S \) initially contains all available possibilities to perform a stopover. Each stopover \( s \in S \) is represented by a specific stopover location \( p^S_s \), a stopover start time \( t^S_s \), a stopover end time \( \bar{t}^S_s \) and a stopover mode \( m^S_s \). The mode represents the restriction that a stopover can only be used by a locker of the corresponding service.

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 \( p^D_d \), a drive end location \( \bar{p}^D_d \), 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 pseudo location \( \gamma \) have to be defined to enable a complete tour. For each \( p \in P \), drives from \( \gamma \) with arrival corresponding to \( T^S_{\gamma p} \) and drives to \( \gamma \) with departure corresponding to \( \overline{T}^S_{p \gamma} \) are created. In addition, the auxiliary parameter \( \sigma_{p, \overline{p}, t} \) indicates the departure time of a particular drive which starts from \( p \) and arrives on time \( t \) at \( \overline{p} \).
Table 2: Sets and Parameters

| \( p \in P \) | → Set of available parking locations |
| \( \gamma \) | → Pseudo 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 \( (t^S) \) and end time \( (t^S) \) |
| \( m^S_s \) | → Mode of stopover \( s \) |
| \( p^S_s \) | → Parking location of stopover \( s \) |
| \( t^S_s \) | → Start time of stopover \( s \) |
| \( t^S_s \) | → End time of stopover \( s \) |
| \( d \in D \) | → Set of drives, for each exists: mode \( (m^D) \), starting location \( (p^D) \), final location \( (p^D) \) and departure time \( (t^D) \) |
| \( m^D_d \) | → Mode of drive \( d \) |
| \( p^D_d \) | → Parking location where drive \( d \) starts |
| \( p^D_d \) | → Parking location where drive \( d \) ends |
| \( t^D_d \) | → Departure time of drive \( d \) |
| \( \sigma_{p,p,t} \) | → \( \sigma \in \mathbb{Z} \) is the departure time at \( p \) to arrive in \( p \) at time \( t \) |
| \( t \in T \) | → Set of discrete points in time |
| \( T^S_p \) | → Set of subsets of \( T \) where a stopover-start exists at parking location \( p \) |
| \( T^S_p \) | → Set of subsets of \( T \) where a stopover-end exists at parking location \( p \) |
| \( T^S_p \) | → 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 \( \gamma \) |
| \( \overline{T}^S_p \) | → 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 \( \gamma \) |
| \( c \in C \) | → Set of customers |
| \( b_{c,d,t} \) | → \( b \in \{0, 1\} \) indicates if a customer \( c \) can be served by a stopover with: \( p, t, t \) |
| \( l \in L \) | → Set of lockers, for each exists: mode \( (m^L) \) and capacity \( (\kappa) \) |
| \( m^L_l \) | → Mode of locker \( l \) |
| \( \kappa_l \) | → Capacity of locker \( l \) |

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 considered, discretized in 1 hour 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 \( T^S_p \) and at least one stopover starts that does not have a prior stopover at the same location \( T^S_{p\gamma} \). In the same way \( T^S_p \) represents points in time at which at least one stopover ends and \( T^S_{p\gamma} \) 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 \( b_{c,p,t} \) indicates whether it is possible to serve a customer \( c \) by a stopover at location \( p \) in the time interval \( t \) to \( \bar{t} \). Finally, the lockers are defined by the set \( L \) and each locker \( l \) has a mode \( m_l \) and a capacity \( \kappa_l \).

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 \( x_{l,p,t}^S \) and which drives \( x_{l,p,t}^D \) are used by the respective lockers \( l \in L \). The mathematical model is as follows.

\[
\begin{align*}
(1) \quad & \max \sum_{l \in L} \sum_{c \in C} y_{l,c} \\
(2) \quad & \sum_{l \in L} y_{l,c} \leq 1 \quad \forall c \in C \\
(3) \quad & \sum_{c \in C} y_{l,c} \leq \kappa_l \quad \forall l \in L \\
(4) \quad & \sum_{s \in S} \sum_{m_s = m_l} b_{c,p,t} \sum_{\bar{t}_s = t} x_{l,p,t}^S \geq y_{l,c} \quad \forall l \in L, c \in C \\
(5) \quad & \sum_{s \in S} \sum_{m_s = m_l} x_{l,p,t}^S = \sum_{d \in D} \sum_{m_d = m_l} x_{l,p,t}^D \quad \forall l \in L, p \in P, t \in T_p^S \\
(6) \quad & \sum_{p \in P} \sum_{t \in T_p^S} x_{l,p,t}^D \leq 1 \quad \forall l \in L \\
(7) \quad & y_{l,c} \in \{0, 1\} \quad \forall l \in L, c \in C \\
(8) \quad & x_{l,p,t}^S \in \{0, 1\} \quad \forall l \in L, p \in P, t \in T, \bar{t} \in T \\
(9) \quad & x_{l,p,t}^D \in \{0, 1\} \quad \forall l \in L, p \in P \cup \{\gamma\}, \bar{p} \in P \cup \{\gamma\}, t \in T \\
(10) \quad & x_{l,p,t}^D \in \{0, 1\} \quad \forall l \in L, p \in P \cup \{\gamma\}, \bar{p} \in P \cup \{\gamma\}, t \in T \\
\end{align*}
\]

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, i.e., 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 $\gamma$ 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.

The essential parts of the presented model are the predefined stopovers, drives, and parameter $b$, which describes whether a customer can be served during a certain stopover or not. The number of stopovers and drives, along with the available lockers, are decisive for the computational complexity of the problem. We apply preprocessing as presented by Schwerdfeger and Boysen (2020) to reduce the problem size without losing optimality. This includes reducing stopovers when they are no option for the actual customers, as well as eliminating non-essential drives.

4.2 Model Adaptations for FPL, MPL, AHD

In the Heterogeneous Locker Location problem, each locker has 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 time $e$ and end at the latest possible time $l$ according to the considered time horizon. Hence, for each FPL location $p \in P_{FPL}$, we create a stopover $(FPL, p, e, l)$, which means a stopover usable by lockers in FPL mode, at location $p$ from $e$ to $l$. Since these lockers are permanently located in one place, no drives are needed, except for the start and end at the pseudo location $\gamma$ for all available locations. Moreover, to define 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 time horizon ($e$ until $l$) 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 $e$ to $l - z$ with $z$ interval steps and $end$ as an element from the set of
Start + z to l with z interval steps. For example, with e = 1:00, l = 4:00 and z = 1 hour, 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 pseudo location γ drives, 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 slightly differently than those of MPL. In this context, the potential AHD locations are the customer locations. Hence, at each AHD location p ∈ PAHD ⊆ P, the earliest possible time ec(p) and latest possible time lc(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 (ec until lc). Thus, stopovers(AHD, p, start, end) are created for each p ∈ PAHD with start as an element from the set of ec(p) to lc(p) − z with z interval steps and end as an element from the set of start + z to lc(p) with z interval steps. For example, a discrete time interval of 20 min and a one-hour customer time window from 1:00 until 2:00 results in six possible stopover time windows {1:00-1:20, 1:00-1:40, 1:00-2:00, 1:20-1:40, 1:20-2:00, 1:40-2:00}. 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.

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 200 customers distributed in an area of 10 km in length and width. Customer locations stem from the VRPTW instances by Gehring and Homberger (1999). 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 customer locations for these instance types are shown in the appendix, see Figure 17-A.

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 – i.e. 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 a maximum of 1 hour length. Flexible customers have four hours to pick up their items and are willing to travel up to 2.5 km to the pickup location.

The temporal distribution of time windows is based on the data by Köhler and Haferkamp (2019) for unequal demand in metropolitan areas and clustered regions. The available time windows span 12 hours (10:00 to 22:00). Since Köhler & Haferkamp considered only two-hour time windows, we distribute/aggregate the demand probabilities equally for one-hour time windows and four-hour time windows. The combined probabilities for customer type and time window preferences are shown in Figure 2. As an example, the probability for a time window from 10:00 to 12:00 according to Köhler & 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 200 compartments, this results in four big lockers with 50 compartments, eight medium lockers with 25 compartments, and ten small lockers with 20 compartments,
respectively. For the combined services, resources are split 50/50, i.e. two fixed and two mobile lockers, four fixed and four mobile lockers, etc.

We assume that each customer location can serve as a stopover location for each service, i.e., each customer location can be visited by AHD. In order to reduce the computational complexity, we use a clustering algorithm to identify smaller sets of locker locations for FPL and MPL. To identify appropriate FPL locations, customer locations were clustered for each instance type according to the number of available lockers (2, 4, 5, 8, 10) with the $k$-medoid algorithm. As a result, customer locations have been assigned such that the distance to the cluster centers (here: locker locations) is minimal for each instance type. To identify reasonable customer locations for MPL, 50 clusters were generated. Thus, it is possible to have a stopover at 25% 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 hours). MPLs can stay at a stopover for 1 to 12 hours. For AHD, the time required for stopovers is set to 10 minutes as various service times ranging from 5 to 20 minutes can be found in the literature (Tilk et al., 2021; Campbell and Savelsbergh, 2006). 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 10-min intervals. For a customer to be served by MPL, the locker must cover the entire pickup time window, i.e. a minimum stopover of 1 hour is required. Hence, if a MPL changes its location, it is not available for service in the corresponding one-hour time slot. Therefore, observed times for repositioning may be higher than the actual times, especially for the MPL service.

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 20 of 720 calculations, no solutions could be found within the maximum runtime of 1 hour, for details see Table 5-A; these 20 cases were excluded from the reported results.

5.2 Results and Discussion

With our computational results, we want to 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, Chapter 5.2.1 provides an overview of the results by generally comparing the
performance of the investigated services. This is followed by a more detailed discussion of
the impact of the instance type characteristics (Chapter 5.2.2), the utilized lockers (Chapter
5.2.3), and the service characteristics for the different customer types (Chapter 5.2.4).
Finally, we briefly discuss a more conservative scenario in Chapter 5.2.5.

5.2.1 Overview

To assess the potential of each of the separate services and service combinations, Figure 3
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 85%. Among single services, AHD performs best with 76%
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 3: Accepted customers for different services](image)

5.2.2 Instance Characteristics

We want to go into more detail and assess the results according to the different charac-
teristics of the instance types. Figure 4 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 3), with FPL showing the smallest acceptance rates (51–59%) and AHD&MPL showing the highest acceptance rates (83–86%). 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 75% 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 5 for separate services and Figure 6 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 6, FPL&MPL reduces the number of customers that had to be rejected due to insufficient distance by FPL. 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.

5.2.3 Locker Characteristics

We now investigate the impact of different numbers of lockers and their compartments. To this end, we consider four big lockers with 50 compartments, eight medium lockers with 25 compartments, and ten small lockers with 20 compartments, as described in Chapter 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 7 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 most 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 acceptance of almost all customers 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 8 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 customer 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: Number of MPL stopovers per locker, for different services and number of lockers (compartments)](image)

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 9 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.

<table>
<thead>
<tr>
<th>Lockers number (compartments)</th>
<th>FPL</th>
<th>MPL</th>
<th>AHD</th>
<th>FPL&amp;MPL</th>
<th>AHD&amp;FPL</th>
<th>AHD&amp;MPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (50)</td>
<td>0%</td>
<td>6.9%</td>
<td>48.5%</td>
<td>0%</td>
<td>9.6%</td>
<td>50.1%</td>
</tr>
<tr>
<td>8 (25)</td>
<td>0%</td>
<td>12.5%</td>
<td>50.0%</td>
<td>0%</td>
<td>19.3%</td>
<td>48.6%</td>
</tr>
<tr>
<td>10 (20)</td>
<td>0%</td>
<td>15.4%</td>
<td>51.1%</td>
<td>0%</td>
<td>21.5%</td>
<td>47.1%</td>
</tr>
</tbody>
</table>

**Impact on Traffic.** Table 3 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 50% 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 13% of the total operating time. For AHD, the travel time remains similar even in the combined services. **In summary, MPL repositioning times are significantly lower compared to AHD. The combination AHD&MPL has a positive effect on the repositioning times per locker when the number of lockers is higher.**

Table 4: Total repositioning time comparison, for different services and lockers

<table>
<thead>
<tr>
<th>Lockers number (compartments)</th>
<th>FPL</th>
<th>MPL</th>
<th>AHD</th>
<th>FPL&amp;MPL</th>
<th>AHD&amp;FPL</th>
<th>AHD&amp;MPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (50)</td>
<td>0 hrs</td>
<td>3 hrs</td>
<td>23 hrs</td>
<td>2 hrs</td>
<td>12 hrs</td>
<td>15 hrs</td>
</tr>
<tr>
<td>8 (25)</td>
<td>0 hrs</td>
<td>12 hrs</td>
<td>48 hrs</td>
<td>9 hrs</td>
<td>23 hrs</td>
<td>29 hrs</td>
</tr>
<tr>
<td>10 (20)</td>
<td>0 hrs</td>
<td>18 hrs</td>
<td>61 hrs</td>
<td>13 hrs</td>
<td>28 hrs</td>
<td>36 hrs</td>
</tr>
</tbody>
</table>

Table 4 shows the results from an absolute perspective, i.e. it reports how many hours all lockers are actually in transit, based on the time-discrete implementation. Using ten lockers, MPL are on the road for 18 hours in total and AHD are creating 61 hours 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 41%.**

**Locker Utilization.** From an economic perspective, it is interesting how well the available resources – different number of lockers with different capacities, i.e. number of compartments – are used. As seen before, 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 want to narrow this down and investigate in which cases capacity limits are the reason for rejection. **Figure 10** 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 about 10 to 20% of lockers at capacity, this increases to 50 or 60% for the AHD combinations. Again, this aligns with the high ratio of customers served.
Figure 10: Percentage of lockers at capacity limit, for different services and number of lockers (compartments)

Figure 11 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 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, but the gap narrows significantly. For AHD&MPL, there is no clear pattern. Limited AHD capacities are more often at 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 AHD. Overall, the capacity utilization seems to be best distributed for AHD&MPL, suggesting that there is further potential to serve additional customers, even though the majority of existing customers have already been served.

Figure 11: Percentage of lockers at capacity limit, for combined services and number of lockers (compartments)
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 12 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.

![Figure 12: Average pickup distance for different services](image)

Some customers may not be serviceable by FPL or MPL at all due to their restricted willingness to travel. Figure 13 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 potentially serviceable customers 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 are not servable 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.

Figure 13: Proportion of non-servable customers per service/service combination

![Bar chart showing the proportion of non-servable customers per service/service combination.](image)

We now consider the acceptance probabilities of customer types by time window for separate services (Figure 14). Note that the one-hour time windows belong to restrictive customers and the four-hour time windows belong to flexible customers. Results for the combined services can be found in the appendix, see Figure 18-A. Overall, restrictive customers have a probability of 57% 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 97% acceptance probability than for MPLs with up to 51%.

Figure 14: Acceptance probability of customers for single services by time window

![Bar chart showing the acceptance probability of customers for single services by time window.](image)
Second, we take a look at the flexible customers on the right side of the Figure 14. 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 99% 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 favoured. For example, customer demand in the 20-21 and 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 15 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 a bit in comparison to separate FPLs.

In summary, in most cases, both customer types benefit from the AHD combinations. Only for AHD&FPL against separate FPLs, the served flexible customers decrease by 1%. By combining AHDs with FPLs or MPLs, it is possible to serve 5% or 7% 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 26% or 19%, respectively. Both customer types benefit most from the combination with MPL.

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. 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, which are served by eight medium-sized lockers.

As Figure 16 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 in R1 instances 30% of the customers 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 7.3 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 chapters, such as less traffic or undesired service, are still in place. Thus, even in the more conservative scenario, the AHD&MPL combination gives 75% of the flexible customers the desired flexibility.

6 Conclusion

We have presented a mixed-integer program 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 considered. Restrictive customers have a limited willingness to travel and shorter pickup time windows, while flexible customers are willing to travel a bit 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 in FPLs result from the selected customer type, in AHDs from the selected time window, and in MPLs, it is a blend of both features.

We see some directions for future research. In the literature, well advanced solution approaches for AHDs are available, but we used a simplified MIP structure to solve it for the sake of simpler comparability. 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 better understanding of the relationship between customer preferences and service offerings.
A  Additional Figures

Figure 17-A: Customer location distributions following Gehring and Homberger (1999)

![Figure 17-A](image)

Table 5-A: Average runtime and GAP for each service, excluding instances with no solution

<table>
<thead>
<tr>
<th>Service</th>
<th>Runtime</th>
<th>GAP</th>
<th>Instances with no solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPL</td>
<td>0.2s</td>
<td>0.00%</td>
<td>0</td>
</tr>
<tr>
<td>FPL&amp;MPL</td>
<td>12.2s</td>
<td>0.00%</td>
<td>0</td>
</tr>
<tr>
<td>MPL</td>
<td>100.9s</td>
<td>0.01%</td>
<td>0</td>
</tr>
<tr>
<td>AHD</td>
<td>2501.6s</td>
<td>8.44%</td>
<td>6xC1; 6xR1; 3xC2; 2xRC1</td>
</tr>
<tr>
<td>AHD&amp;FPL</td>
<td>1559.2s</td>
<td>0.73%</td>
<td>1xC1</td>
</tr>
<tr>
<td>AHD&amp;MPL</td>
<td>2060.9s</td>
<td>1.43%</td>
<td>1xC1; 1xR1</td>
</tr>
</tbody>
</table>

Figure 18-A: Acceptance probability of customers for single services by time window
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