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Integrating mobile parcel lockers into last-mile delivery networks: an operational design for home delivery, stationary, and mobile parcel lockers

Marcel Peppel and Stefan Spinler
WHU-Otto Beisheim School of Management, Institute for Logistics Management, Vallendar, Germany, and
Matthias Winkenbach
Megacity Logistics Lab, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Abstract

Purpose – The e-commerce boom presents new challenges for last-mile delivery (LMD), which may be mitigated by new delivery technologies. This paper evaluates the impact of mobile parcel lockers (MPL) on costs and CO_2 equivalent (CO_2e) emissions in existing LMD networks, which include home delivery and shipments to stationary parcel lockers.

Design/methodology/approach – To describe customers' preferences, we design a multinomial logit model based on recipients' travel distance to pick-up locations and availability at home. Based on route cost estimation, we define the operating costs for MPLs. We devise a mathematical model with binary decision variables to optimize the location of MPLs.

Findings – Our study demonstrates that integrating MPLs leads to additional cost savings of 8.7% and extra CO_2e emissions savings of up to 5.4%. Our analysis of several regional clusters suggests that MPLs yield benefits in highly populous cities but may result in additional emissions in more rural areas where recipients drive longer distances to pick-ups.

Originality/value – This paper designs a suitable operating model for MPLs and demonstrates environmental and economic savings. Moreover, it adds recipients' availability at home to receive parcels improving the accuracy of stochastic demand. In addition, MPLs are evaluated in the context of several regional clusters ranging from large cities to rural areas. Thus, we provide managerial guidance to logistics service providers how and where to deploy MPLs.

Keywords Last-mile delivery, Mobile parcel locker, Mixed delivery setup, Parcel locker location, Regional delivery distribution, Mathematical model with binary decision variables

Paper type Research paper

1. Introduction

E-commerce sales are projected to reach USD 6,388 billion in 2024, which means that the sector will have quintupled in ten years (Statista, 2020b), with a corresponding increase in parcel shipments. This tremendous growth has been accelerated by the COVID-19 pandemic

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and is likely to continue as consumers are more willing to purchase goods online (Coppola, 2021; UPS, 2021). For instance, UPS (2021) finds that consumers' preference for buying products in-store has decreased from 54% to 40%. This change in consumer behavior has transformed the last-mile delivery (LMD) sector. Some logistics service providers (LSP) have initiated same-day delivery (Ulmer, 2020). However, start-ups have entered the market, offering specialist services such as delivery of groceries within ten minutes (e.g. Gorillas and Flink) and delivery of beverages to the doorstep within two hours (e.g. Flaschenpost) (Flaschenpost, 2023; Flink, 2023; Gorillas, 2023).

Nevertheless, the LMD sector is very competitive and margins are low because LMD is recognized as the most costly element of total shipping costs, accounting for 41–50% of these costs (Jacobs *et al.*, 2019; Joerss *et al.*, 2016). In addition, LMD has adverse effects, such as increasing CO_2 equivalent (CO_2e) emissions and congestion, and negative impacts on health (Amaya *et al.*, 2021; Giordano *et al.*, 2018). For instance, CO_2e emissions associated with the global transportation sector increased by 80% in roughly 30 years, amounting to 8.26 billion tons in 2018 (Statista, 2020a), and 4.8% of worldwide greenhouse gas emissions are generated by road freight traffic (Ritchie and Roser, 2020).

Furthermore, slow identification of handover points and the not-at-home problem pose additional challenges in the LMD sector (Allen *et al.*, 2018; Gevaers *et al.*, 2011). Thus, LSPs have developed strategies and new products to cope with these challenges. For instance, LSPs can improve their cost efficiency by increasing drop factors and decreasing stop factors, combined with route optimization using new artificial intelligence features (Chung, 2021). They have already tested and deployed new delivery technologies to reduce CO_2e emissions, such as cargo bikes (McLeod *et al.*, 2020; Moncef and Dupuy, 2021) and electric delivery vehicles (DHL, 2021b; Kirschstein, 2020). Solutions to other LMD obstacles have also been tested, including autonomous delivery vehicles (Lemardelé *et al.*, 2021; Liu *et al.*, 2021), delivery bots (Bakach *et al.*, 2020; Chen *et al.*, 2002, 2021; Pani *et al.*, 2020), crowdsourced delivery (Arslan *et al.*, 2019; Horner *et al.*, 2021), delivery to neighbors (Akeb *et al.*, 2018), drones (Agatz *et al.*, 2018; Dayarian *et al.*, 2020; Moshref-Javadi *et al.*, 2020), mobile depots (Hof and Schneider, 2021; Marujo *et al.*, 2018), order consolidation (Zhang *et al.*, 2019) and delivery to trunks of cars (Reyes *et al.*, 2017). Several studies provide overviews of LMD technologies (e.g. Allen *et al.*, 2018; He, 2020; Mangiaracina *et al.*, 2019; Savelsbergh and Van Woensel, 2016).

The concept of stationary parcel lockers (SPL), which refers to automated, unsupervised pick-up points (Deutsch and Golany, 2018; Wang *et al.*, 2019), is now widely dispersed. These are often located in places with high transit traffic, for example in supermarkets or at gas stations, where consumers can access their parcels at any time using built-in touchscreens or apps (Deutsch and Golany, 2018; Schwerdfeger and Boysen, 2020). LSPs have deployed this technology worldwide, including in Asia (Jiang *et al.*, 2019; Lin *et al.*, 2020; Yuen *et al.*, 2019), Europe (Iwan *et al.*, 2016; Morganti *et al.*, 2014b), and North and South America (Deutsch and Golany, 2018; De Oliveira *et al.*, 2017). For instance, more than 400,000 SPLs were in operation in China in 2019 (Wang *et al.*, 2020b). Research has demonstrated the benefits to LSPs of using SPLs, such as better delivery success rates, fewer traveled kilometers, and reductions of up to 16% in operational expenses (Lee *et al.*, 2019; Morganti *et al.*, 2014a, b; Van Duin *et al.*, 2020). SPLs will remain an integral part of LMD in the future (Peppel *et al.*, 2022).

However, new companies, such as Cainiao, Cleveron, and NURO, have recently emerged, introducing the concept of mobile parcel lockers (MPL) (Harper, 2020; Cleveron, 2021; Nuro, 2023). As an evolution of SPLs, MPLs are autonomous LMD vehicles with compartments for goods and can reach customers in closer proximity (Figliozzi, 2020; World Economic Forum, 2020). Figure 1 presents examples for SPLs and MPLs. Most MPL suppliers are currently conducting field tests, and Cainiao has plans to deploy more than 10,000 MPLs in China (Harper, 2020), but little academic research has addressed this concept.

As illustrated previously, LMD is costly and has adverse effects on the environment. In this paper, we address the effect of MPLs on LMD networks by designing a functional operating model for MPLs. We build a network design problem that covers MPLs next to regular home delivery and SPL delivery. Our network design problem accounts for recipients' stochastic demand and covers the routing of MPLs across different regional settings ranging from rural areas to large cities. To guide LSPs, we investigate the economic and environmental impacts of integrating MPLs into LMD networks and answer the following research questions:

RQ1. What are the economic and environmental impacts of MPLs?

RQ2. In which regional settings ranging from rural areas to large cities should MPLs be utilized?

RQ3. What role will MPLs play in the future growth of LMD networks?

We contribute to LMD research by formulating a holistic network for LMD, including home, SPL, and MPL delivery. This model determines near-optimal deployment locations for MPLs and MPL stops to reduce the environmental and economic impacts of delivery services, using a mathematical model with binary decision variables. The economic impact refers to the cost of LMD of an item using such a network, while the environmental impact relate to the associated CO_2e emissions. Customer choices on parcel locker delivery are integrated with a multinomial logit (MNL) model. We apply the LMD network problem to a real-life dataset of a global LSP comprising approximately 750,000 shipments. We also conduct sensitivity analyses and investigate a growth case, which illustrates the case of higher demand.

In the remainder of this paper, Section 2 presents an overview of related literature, and Section 3 introduces the MNL model, route cost estimation, and mathematical model with binary decision variables formulation. In Section 4, the results of our empirical study are presented and discussed, as well as its managerial implications are highlighted. Finally, Section 5 draws some conclusions and suggests avenues for further research.

Figure 1.
DHL's SPL (left) and Cleveron's MPL (right)

Note(s): Pictures used with permission of Deutsche Post DHL Group and Cleveron AS, respectively

2. Literature review

The extant literature focuses mainly on SPLs while research on MPLs is very limited. In this section, we review current research on these two technologies.

2.1 Stationary parcel lockers

SPL technology is highly diffused, being used in more than 20 countries (Deutsch and Golany, 2018). Research focuses on three main topics. The first stream of studies investigates customers' acceptance of SPLs and decision criteria in various regions, including Asia, Australia, Europe as well as North and South America (Iwan *et al.*, 2016; Lachapelle *et al.*, 2018; Morganti *et al.*, 2014b; De Oliveira *et al.*, 2017; Vakulenko *et al.*, 2018; Weltevreden, 2008; Yuen *et al.*, 2019). These demonstrate that travel distance to SPLs is a crucial decision criterion for recipients (Iwan *et al.*, 2016; De Oliveira *et al.*, 2017). Other criteria investigated include accessibility, ease of use, reliability, and safety, although SPL users consider these to be less relevant (Iwan *et al.*, 2016; Lee *et al.*, 2019; De Oliveira *et al.*, 2017).

The second research stream finds that if SPL locations were improved, more than 15% of recipients would use SPLs more often (Lemke *et al.*, 2016). Acknowledging the high importance of SPL sites, some studies focus on optimizing their locations. Deutsch and Golany (2018) build an integer linear programming model of a network with 100 nodes optimizing SPL locations and maximizing total profits. They assume deterministic customer demand without capacity restrictions. In a similar study that includes routing, medication is delivered to either SPLs or homes to optimize delivery costs (Veenstra *et al.*, 2018). In addition to optimizing costs, Lin *et al.* (2020) build an SPL location problem to maximize service levels. To account for recipients' stochastic demand, they create an MNL model based on clients' distance to SPLs.

The third strand of research investigates the environmental effects of SPLs. Giuffrida *et al.* (2016) reveal that SPLs can generate emissions savings of up to 66%, assuming that no emissions are generated during the pick-up process. Their sensitivity analysis shows that SPLs result in more CO_2e emissions if the travel distance by car exceeds approximately one kilometer (Giuffrida *et al.*, 2016). Kiousis *et al.* (2018) analyze reductions in delivery vans' travel time and distance, finding reductions of up to 82.4% and 90.9%, respectively.

Prandtstetter *et al.* (2021) examine SPLs in rural and suburban settings, including emissions from both deliveries and pick-ups. They show that SPLs can generate CO_2 savings of up to 40% (Prandtstetter *et al.*, 2021). In a related study, Ji *et al.* (2019) design a model to reduce the operating and energy costs of fixed SPLs. Peppel and Spinler's (2022) study combines cost and environmental aspects. Based on recipients' availability at home and travel distance to SPLs, they devise an MNL model to find optimal SPL locations that minimize total costs and CO_2e emissions. Their study reveals that optimized SPL locations produce savings of up to 11.0% in costs and 2.5% in emissions.

Nevertheless, SPLs also have some drawbacks. Owing to their fixed locations, their ability to respond to changes in demand is limited (Wang *et al.*, 2020b). Furthermore, LSPs must negotiate contracts with several parties, such as supermarket or gas station chains and public institutions, to build SPLs on their grounds. MPLs might overcome these challenges.

2.2 Mobile parcel lockers

A few recent studies have examined the concept of MPLs. Schwerdfeger and Boysen (2020) build a model to optimize shifts in MPL locations based on customers' temporary locations. Their study reveals that fewer MPLs than SPLs are necessary to meet recipients' needs, in terms of total demand for parcel locker delivery. In their model, MPLs are either moved manually by LSP personnel or are autonomous.

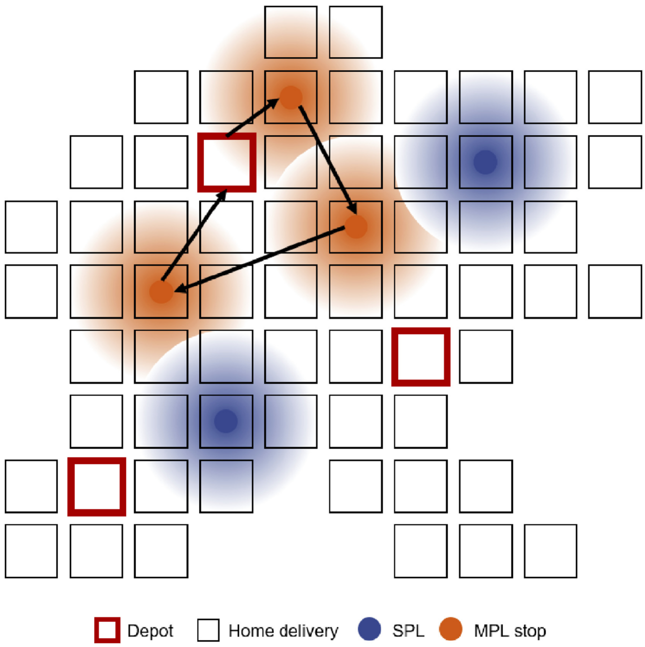
Wang *et al.* (2020a) devise a non-linear integer programming model to minimize costs while optimizing the locations and routes of MPLs. Their model identifies the required number of MPLs and the service time in a distribution network with 32 nodes. They compare two cases. In the first, all demand points are addressed individually, i.e., MPL delivery is used in the sense of autonomous home delivery. In the second, demand points are pooled into distribution points, reducing the number of MPL stops. The results show that operation times are about 44% higher in the first case than in the second, whereas the delivery costs of the two options differ only slightly.

Further, Wang *et al.* (2020b) determine MPL stops per day under stochastic demand based on maximum walking distance, minimizing operating costs. They find that the number of parcel compartments and the maximum walking distance are key factors influencing the optimal solution. They conclude that MPLs with many compartments in combination with few MPL stops can reduce operating costs substantially, whereas MPLs with few compartments should be used for dispersed demand points.

In a related context, Beirigo *et al.* (2018) demonstrate that mixed-purpose fleets for both parcel shipments and passenger transportation perform better than single-purpose fleets. Moreover, Li *et al.* (2021a) interpret MPLs as intermediaries between depots and couriers and build a model to determine MPL and courier routes. This hybrid model allows couriers to remain in the field, eliminating the need for replenishment at the depot during the day and extending the depots' range.

3. Methodology

This section describes our process of building a holistic LMD service that incorporates the delivery points (i.e., homes, SPL, and MPL) that represent the nodes of network for LMD, while the arcs would represent the roads connecting the delivery points. Figure 2 illustrates



Source(s): Own illustration

Figure 2.
Illustration of the LMD network

an LMD network that includes all three delivery modes. We split cities into uniform squared segments. Current SPL locations are used, and real-life depots act as hubs for MPLs, which travel to multiple stops throughout the day. Recipients can use parcel lockers in nearby segments.

We follow a three-step process to determine the effect of integrating MPLs into an LMD network. First, residents in each segment have a certain probability of choosing parcel locker delivery. To describe discrete customer choices for parcel locker or home delivery, we devise an MNL model. Second, we develop an approach to estimate the route costs of MPLs, including purchase and replenishment costs. Third, we formulate a mathematical model with binary decision variables to determine eligible depots that should operate MPLs and suitable MPL stops in order to minimize total LMD network costs, including economic and environmental components.

3.1 Multinomial logit model

MNLs have been applied successfully in previous research (Aros-Vera *et al.*, 2013; Lin *et al.*, 2020; Zhang and Atkins, 2019). For instance, Lin *et al.*'s (2020) study relies on an MNL model as an input to find SPL locations that optimize overall service levels. Their MNL model and corresponding probability of parcel locker delivery are based on recipients' travel distance to SPLs.

Travel distance has been identified as the most crucial criterion for SPL usage (Iwan *et al.*, 2016; Lemke *et al.*, 2016). In addition, our model includes customers' availability at home in line with Peppel and Spinler (2022). With this additional component, we extend current MNL models to address the not-at-home problem for LMD, which leads to high failure rates for first-time deliveries. Absent recipients, who may be working shifts or on vacation, may be more likely than other recipients to favor receiving shipments via SPLs or MPLs.

In our MNL model, we make three assumptions. First, since MPLs remain at locations for a limited time, some recipients may be less likely to use MPLs than SPLs. However, other recipients may benefit from MPL stops being closer than their nearest SPLs, making them more likely to prefer the former. We have no information about recipients' preferences about a restricted pick-up time horizon or pick-up distance. Together with our industry partner, we decided to abstract from this factor and assume that the time constraint and the shorter distance offset each other. The actual impact is difficult to evaluate, so we assume that recipients are indifferent to receiving parcels via either SPLs or MPLs. Consequently, recipients have two delivery options: home or parcel locker delivery. Second, we suppose that recipients' preferences are constant over time. Third, our data comprise shipment volumes per location, making it impossible to differentiate between residents living in the same building, who are therefore classified as single residents.

We devise our MNL model in line with McFadden's (1974) and Peppel and Spinler (2022) approach. Table A1 of Appendix explains the notation. Recipient n will maximize utility U_{pn} when selecting a parcel delivery service. The utility can be determined for both parcel locker delivery (U_{pn}) and home delivery (U_{hn}) and is based on a deterministic component of the utility (i.e. V_{pn} or V_{hn}) and a stochastic component as a random error term (i.e. e_{pn} or e_{hn}) which is gumbel distributed:

$$U_{pn} = V_{pn} + e_{pn} \quad \text{and} \quad U_{hn} = V_{hn} + e_{hn}, \ \forall \ n \in N. \tag{1}$$

The deterministic component of the utility reflects recipients' travel distance to parcel lockers and availability at home: recipients will select the delivery option from their choice set C that provides the higher utility (Temme, 2007; Train, 2009). The probability of recipient n choosing parcel locker delivery p and home delivery h is:

$$P_{pn} = \frac{e^{V_{pn}}}{e^{V_{pn}} + e^{V_{hn}}} \quad \text{and} \quad P_{hn} = 1 - P_{pn} \; . \tag{2}$$

In the next step, we aggregate the individual recipient probabilities residing in one segment into an average probability for each segment with $\phi_{ip} = \sum_{n=1}^{n_p} \frac{e^{V_{pn}}}{n_p}$ and $\phi_{ih} = \sum_{n=1}^{n_h} \frac{e^{V_{hn}}}{n_h}$. Thus, the probability of choosing parcel locker delivery p or home delivery h in segment i is:

$$\omega_i = \frac{\phi_{ip}}{\phi_{ip} + \phi_{ih}} \quad \text{and} \quad \lambda_i = 1 - \omega_i. \tag{3}$$

3.2 Route cost estimation

The literature on location routing problems (LRP) offers a range of exact and approximate solution methods (for a comprehensive overview, see Nagy and Salhi, 2007; Drexl and Schneider, 2015; Schneider and Drexl, 2017). Routing costs traditionally include facility costs and capacity constraints, while more recent studies also integrate facilities' handling fees (Janjevic *et al.*, 2019). Since real-life problems often consider several thousand demand points in cities, finding exact solutions for LRPs is considered very computation- and time-intensive. In addition, parcel shipments and corresponding demand points are subject to daily changes, exacerbating exact location routing (Janjevic and Ndiaye, 2014). Thus, continuum approximations, i.e., closed-form route length estimations, can be used instead, which yield near-optimal solutions based on limited information (Daganzo, 1984; Smilowitz and Daganzo, 2007).

Winkenbach *et al.* (2016) design an augmented route cost estimation formula that includes several capacity and service-time constraints. We adapt their approach to determine the costs of dedicated MPL routes. Although they formulate a route cost estimation for a multi-echelon LRP, both approaches follow the same methodology by relying on continuum approximation. We formulate our route cost estimation as follows:

$$f_j = c^r + f^m + n_j t^a c^p + (n_j + 1)\left(t^d c^d\right), \tag{4}$$

$$\text{where} \quad n_j = min\left[\delta_j, \xi_j\right], \tag{5}$$

$$\delta_j = \left\lfloor \frac{T^{max} - t^s - t^d}{t^a + t^d} \right\rfloor, \tag{6}$$

$$\xi_j = \left\lfloor \frac{C_j^M}{\rho} \right\rfloor, \tag{7}$$

$$t^d = \frac{\kappa}{v\sqrt{\gamma}}, \tag{8}$$

$$c^d = c^e e^c + c^h \tau \; . \tag{9}$$

In Eq. 4, routing costs f_j are estimated based on several components (see Appendix, Table A2 for a summary of additional notation). The first and second components refer to the daily replenishment costs of the MPL at depot c^r and daily fixed MPL costs including maintenance and rent f^m. The third term represents the operating costs at pick-up locations, as a product of the number of stops, service time, and MPL operating costs at pick-up locations. The last term embodies MPL operating costs incurred while driving between multiple MPL stops and the depot.

The routing costs f_j rely on the number of stops, which depend on time constraints δ_j and capacity ξ_j constraints (see Eq. 5). To determine the maximum number of stops on a tour, Eq. 6 builds the quotient of the residual time for visiting MPL stops (i.e., the difference between the maximum time $T^{\max}$, the setup time per tour t^s, and the inter-stop travel time to the first stop t^d) and the sum of the service time per stop t^a and the inter-stop travel time t^d. The service time per stop t^a will influence the utility of recipients. The key focus of this paper is to develop a potential operating model of MPLs for LSPs and demonstrate potential environmental and economic savings when deploying MPLs. Integrating parking duration, i.e., service time, as an internal model parameter increases the complexity operating MPLs tremendously for LSPs. We discussed this topic with our industry partner who outlined that a fixed service time per stop is more practical. Furthermore, ξ_j (see Eq. 7) refers to the capacity constraint based on the quotient of maximum MPL capacity C_j^M and drop factor ρ. Eq. 8 determines the travel time between two stops based on the quotient of circuity factor κ and the average MPL velocity v while driving as well as stop density γ. Finally, Eq. 9 presents the operating costs during MPL driving. These are composed of the energy costs and the cost of personnel who observe the MPLs from remote locations and intervene in case of difficulties.

We initially estimated each parameter based on desk research and validated them with our undisclosed LSP partner. Closer analysis of the term revealed that handling costs c^r, daily fixed MPL costs f^m, and personnel costs c^h account for more than 99% of expenses covered by the routing cost formula. In contrast, energy costs as part of the operating costs are very low accounting for less than 1% so that we decided to neglect them. The term collapses to:

$$f_j \approx c^r + f^m + (n_j + 1)\left(t^d c^h \tau\right) . \tag{10}$$

3.3 Model formulation

To integrate MPLs into the LMD network, we design an optimization model that minimizes economic and environmental costs. In other contexts, some studies design a multi-objective approach (Hamdy *et al.*, 2011; Cao *et al.*, 2021). However, we choose a single-objective approach since economic savings are the essential criterion for LSPs to adapt their operations. Furthermore, Peppel and Spinler's (2022) single-objective approach yields very similar results compared to a CO_2e optimal solution.

The model considers three delivery modes: home, SPL, and MPL delivery. In contrast to previous studies (Deutsch and Golany, 2018; Lin *et al.*, 2020), we focus on integrating MPLs and deriving the near-optimal number of MPLs, deployment locations, and MPL stops. Decision variable $y_{l,j}$ indicates whether candidate segment $l \in I$ is activated as an MPL stop served from depot j. In our model, MPLs start and end their tours at depot j, with associated candidate segments l for MPL stops (see Appendix, Table A3 for additional notation). We formulate the LMD network problem as a mathematical model with binary decision variables:

$$\min_{y_{l,j}} K^T\left(y_{l,j}\right) = K^H + K^S + K^M\left(y_{l,j}\right), \tag{11}$$

$$\text{where} \quad K^H = \sum_{i \in I} V_i^H\left(s_i^H\left(V_i^H\right) + e_i^H\left(V_i^H\right)\right), \tag{12}$$

$$K^S = \sum_{i \in I} x_i\left(f^S + o^S + e^o\right) + \sum_{k \in I} V_k^S\left(s_k^S + e_k^S + e^r g_k d^a\right), \tag{13}$$

$$K^M(y_{l,j}) = \sum_{j\in J}\left(min\left[\sum_{l\in L} y_{l,j}, 1\right] f_j + \sum_{l\in L} y_{l,j} V_l^M e^r g_k d^a\right), \tag{14}$$

$$V_i^H = V_i - V_k^S - V_l^M, \text{for } k \in I, l \in I, \tag{15}$$

$$V_k^S = \begin{cases} V_k \omega_k \epsilon_{ik} & \text{for } C_i^S \geq \sum_{k\in K} V_k \omega_k \epsilon_{ik}, \\ C_i^S \dfrac{\omega_k \epsilon_{ik} V_k}{\sum_{k\in K} \omega_k \epsilon_{ik} V_k}, & \text{otherwise}, \end{cases} \tag{16}$$

$$V_l^M = \begin{cases} y_{l,j} \sum_{k\in K} V_k (\omega_k - \mu_k) \epsilon_{ik} & \text{for } C_i^{M,R} \geq \sum_{k\in K} V_k (\omega_k - \mu_k) \epsilon_{ik}, \\ y_{l,j} \sum_{k\in K} C_i^{M,R} \dfrac{(\omega_k - \mu_k) \epsilon_{ik} V_k}{\sum_{k\in K} (\omega_k - \mu_k) \epsilon_{ik} V_k}, & \text{otherwise}, \end{cases} \tag{17}$$

$$\epsilon_{ik} = max[-\eta d_{ik} + 1, 0], \tag{18}$$

$$\eta = \frac{1}{\frac{r^{max}}{z} + 1}, \tag{19}$$

$$s_i^H(V_i^H) = min\left[s^H \frac{1}{(V_i^H)^a} + s^H, s^{Hmax}\right], \tag{20}$$

$$e_i^H(V_i^H) = min\left[e^H \frac{1}{(V_i^H)^a} + e^H, e^{Hmax}\right], \tag{21}$$

$$\text{s.t.} \quad 0 \leq \omega_k \leq 1 \ \forall \ k, \tag{22}$$

$$0 \leq \mu_k \leq \omega_k \ \forall \ k, \tag{23}$$

$$\sum_{l\in L} y_{l,j} \leq n_j \ \forall \ j, \tag{24}$$

$$\sum_{k\in K} V_k^S \leq C_i^S \ \forall \ i, \tag{25}$$

$$y_{l,j} \in \{0, 1\} \ . \tag{26}$$

The total costs K^T of the LMD network, consisting of home, SPL, and MPL delivery expenses, are minimized (Eq. 11). The costs of each delivery mode are defined individually. Costs of home delivery K^H are determined per segment i based on the specific shipping volume V_i^H, shipping costs s_i^H, and environmental costs e_i^H, adjusted by surcharge factors depending on the shipping volume (Eq. 12). The surcharge factors account for additional delivery costs for LSPs if the volume of home delivery in segment i is low owing to lower recipient density for this kind of delivery service, i.e., the delivery of shipments becomes more expensive per parcel in this delivery mode. In other words, the more parcels delivered via home delivery, the lower the surcharge factor (Eq. 20-21). These values were calibrated with our industry partner (Peppel and Spinler, 2022) and capped to assign maximum surcharges. Eq. 13 presents the costs of SPL delivery. These comprise the fixed, operating, and emissions costs incurred for the number of SPLs in the LMD network, as well as shipping and emissions costs for SPL delivery in segments $k \in I$ served by SPL delivery. Emissions generated by recipients' pick-ups are also added. The MPL delivery costs $K^M(y_{l,j})$ comprise the MPL route cost estimation and pick-up costs (Eq. 14). This term activates the MPL route costs f_j if at least one MPL stop l in the catchment area is assigned to depot j. The second term represents the emissions costs of parcel pick-ups by recipients.

The shipment volume for home delivery V_i^H is determined by the difference between the total shipments to segment V_i and the shipment volume served by SPL V_k^S and MPL delivery V_l^M (Eq. 15). To allocate demand to an SPL, we assume that parcel lockers attract demand from their own and neighboring segments, defined as $k \in I$. We premise that recipients' willingness to use a particular parcel locker decreases with travel distance. Consequently, we define the slope η of the decay function (Eq. 19) based on the maximum number of layers (i.e. quotient of maximum radius $r^{\max}$ and edge length z) around a parcel locker to derive demand adjustment factor ϵ_{ik} (Eq. 18). For instance, a shorter distance between the parcel locker and the demand segment leads to only small reductions in parcel locker demand and vice versa. Thus, the shipping volume allocated to SPL V_k^S is either the adjusted demand for parcel locker delivery if the SPL's capacity is sufficient or the proportionate share of the SPL's capacity (see Eq. 16). Similarly, the volume assigned to MPL delivery V_l^M is calculated if an MPL stop $y_{l,j}$ is activated. However, demand for parcel locker delivery will be updated based on the portion already served by SPL delivery, and the residual MPL capacity after each stop $C_i^{M,R}$ will be used (Eq. 17).

Some constraints limit the model. The probability of parcel locker demand ω_k ranges between 0 and 1 (Eq. 22), and the proportion of recipients already served by SPL delivery μ_k ranges between 0 and ω_k (Eq. 23). The sum of MPL stops $y_{l,j}$ associated with depot j cannot exceed the maximum number of MPL stops per tour n_j (Eq. 24). Moreover, the sum of SPL demand served in candidate segments cannot exceed the SPL's capacity C_i^S (Eq. 25). The domain of the decision variable $y_{l,j}$ is binary (Eq. 26).

We compute a solution to the mathematical model with binary decision variables based on the following assumptions, which we defined with our industry partner. First, the maximum pick-up distance $r^{\max}$ is adjusted to city size. Having evaluated recipients' pick-up distances and selected a distance applicable to 90% of recipients, we include the majority of recipients while omitting outliers. We fix $r^{\max}$ in steps of z. For example, if $z = 0.5$, then $r^{\max}$ is a multiple of z, e.g. 0.5, 1.0, 1.5. Second, the existing SPL network first satisfies demand for parcel locker delivery, with MPLs serving residual demand. This assumption reflects the status of most LSPs with an SPL network and was confirmed by our industry partner. Third, some SPL users do not collect their parcels the same day they are shipped to the preferred SPL. Thus, a specific proportion of SPL compartments is constantly occupied. Based on our industry partner's experience, we set the share of occupied SPL compartments to 30%. Since we assume that MPL users collect all parcels within the service time per stop, the MPL is empty before a new tour. Fourth, we assume that MPLs' capacity will be maximally exploited per stop, leading to residual MPL capacity for the subsequent stop.

Furthermore, we defined the following parameter values based on data and insights from our industry partner. First, like Rautela *et al.* (2021), we assume that demand points for parcel shipments are uniformly distributed in each segment. Second, we only consider parcels of medium size, since the data provided by our industry partner do not include more detailed information. Third, we assume that MPLs' battery life and range can serve a daily tour and that electricity used during the operation of parcel lockers is generated in an eco-friendly way, excluding potential emissions during manufacturing and recycling processes. Much political effort is being devoted to this issue, such as the "European Green Deal" (European Commission, 2021). Hence, MPLs and battery electric vehicles (BEV) are CO_2e emission-neutral. However, only 0.3% of vehicles in public fleets (KBA, 2020) and 25% in LSP fleets (based on information of our industry partner) are BEVs, leading to emissions for their counterparts. Fourth, depot locations refer to real-life post offices, which serve as hubs for MPLs. No additional costs are incurred for operating the depot system since we build on a pre-established depot network. In addition, to reduce complexity, only one MPL is assigned per depot, and it must complete a round trip within a day. Designated MPLs are maintained and replenished at the depots.

3.4 Solution method

Our proposed solution method focuses on identifying the near-optimal MPL configuration with suitable MPL stops, minimizing total LMD network costs $K^T(y_{l,j})$, as described in the mathematical model with binary decision variables' objective function in Eq. 11. Deriving the exact optimal solution method would cause substantial computation complexity and solution times. For this reason, we apply a greedy heuristic to select eligible MPL stops. In each computation step, MPL stops are chosen that yield the maximum cost advantage. After determining the MPL stop with the highest saving potential, the setup is updated accordingly. Algorithm 1 provides a high-level synopsis of our suggested solution method. In the next paragraphs, we briefly introduce the solution method.

In the beginning, we initialize vectors of total demand for shipments V and home delivery H, as well as demand for parcel locker delivery D, and create empty vectors containing SPL and MPL delivery information, i.e. V^S and V^M (line 1). In lines 2 and 3, we initialize basic information, such as the assigned edge length z of segments in a city, and the slope of decay function η to adjust demand per distance layer. As the baseline, we compute the total costs K^T* for 100% home delivery (line 4).

The next part iterates through the list of real-life SPLs and allocates demand for parcel locker delivery D to neighboring segments k (line 5). Adjacent segments k for each SPL are identified based on the maximum number of layers (line 7). To update demand, we distinguish whether the SPL can cover the total demand volume for parcel locker delivery, or whether the SPL's capacity is lower than the demand and must be adjusted accordingly. Relevant vectors are updated (lines 8–17). Based on the new information, the total costs K^T* comprise home and SPL delivery (line 18).

In the final step, we integrate MPLs into the LMD network. Since one MPL can be assigned per depot j, we use total enumeration of all depot locations (line 19), since the maximum number of MPL stops per MPL is limited by n_j. We create a matrix of candidate MPL stops l based on the MPL's full driving range (line 20). Each candidate stop in the catchment area of depot j is evaluated, and up to n_j stops leading to the highest savings potential are added to the LMD network. The parameters of the *update demand* function are adapted to the MPL case (lines 21–23). Finally, the near-optimal costs for the entire LMD network are calculated, including home, SPL, and MPL delivery (line 24).

Algorithm 1. Solution method

Data: $V_i,\ \omega_i,\ X\ ,\ J$

Result: K^T, V^H, V^S, V^M

Initialize vectors V (parcel volume), D (demand), H (home delivery), V^S (SPL delivery), and V^M (MPL delivery)

Define edge length z for quadratic segments

$\eta \leftarrow \frac{1}{\frac{r^{max}}{z}+1}$ ▷ Determine the slope of the decay function

Update $K^{T*} = K^H$ ▷ Determine costs if the entire network is serviced by home delivery

for $x \in X$ **do**

  Function UPDATE DEMAND

    Identify neighboring segments

    if $\sum_{k\in K} V_k\omega_k\epsilon_{ik} \leq C^S$ **then**

      $V_k^S \leftarrow V_k\omega_k\epsilon_{ik}\ \forall\ k \in K$ ▷ Update vector V^S with new values for segments k

      $D \leftarrow D - V_k^S$ ▷ Update demand vector by deducting served parcel locker demand

      $H \leftarrow H - V_k^S$ ▷ Update home delivery vector by deducting served parcel locker demand

      $C^S \leftarrow C^S - V_k^S$ ▷ Update residual capacity by deducting served parcel locker demand

    else

      $V_k^S \leftarrow C^S \frac{V_k\omega_k\epsilon_{ik}}{\sum_{k\in K} V_k\omega_k\epsilon_{ik}}$ ▷ Update vector V^S with new values for segments k

      $D \leftarrow D - V_k^S$ ▷ Update demand vector by deducting served parcel locker demand

      $H \leftarrow H - V_k^S$ ▷ Update home delivery vector by deducting served parcel locker demand

      $C^S \leftarrow C^S - V_k^S$ ▷ Update residual capacity by deducting served parcel locker demand

Update $K^{T*} = K^H + K^S$ ▷ Determine costs if entire network is serviced by home and SPL delivery

for $j \in J$ **do**

  Create a matrix of candidate MPL stops l associated with depot j to activate up to n_j stops

  for $r \in n_j$ **do**

    Select candidate stop $y_{l,j}$ with the highest savings potentials

    UPDATE DEMAND ▷ Adapt to MPL: update vector V^M and use residual MPL capacity $C_i^{M,R}$

Update K^{T*} ▷ Suitable MPL stop locations are integrated to generate cost savings

4. Case study

We partnered with a global LSP to evaluate the impact of MPLs on LMD networks based on our formulated model. This section presents the results of the base case and additional sensitivity analyses. Since the volume of parcel shipments will continue to grow (Statista, 2019), we also build a growth case and illustrate the impact of MPLs. Finally, we discuss our findings in relation to our research questions and highlight their managerial implications for LSPs.

4.1 Case study dataset

Our undisclosed industry partner in the LMD sector shared a dataset that contains regular shipment data, without large deviations for periods such as Christmas, Black Friday, or singles' day. The dataset covers three weeks of February 2019 for a European country and contains 742,457 parcel shipments. It is the same dataset as used by Peppel and Spinler (2022).

The data cover 15 cities in various regions and with differing population densities to illustrate geographical differences. Table 1 presents the selected cities while Table 2 reveals more information about the data, i.e., population density, demand point density, and shipment density per square kilometer (Peppel and Spinler, 2022). In the base case, we cover all cities in our study, whereas further analyses focus only on cities B and E, two cities selected from the most prominent regional clusters to evaluate changes in greater detail and reveal more granular changes. Furthermore, the dataset comprises shipments to homes, SPLs, and post offices. We suppose that recipients prefer post office and parcel locker delivery equally, since we presume that recipients choose locations closest to their homes. Thus, we classify shipments to post offices as parcel locker deliveries. All demand points for a city are assigned to squared segments of equal size, with an edge length z of 0.5 kilometers. In addition, we gathered details of the locations of real-life SPLs and post offices as hubs for MPLs. Our industry partner conducted a survey of 838 SPL users across all regional clusters so that we know the extent to which recipients' parcel pick-ups generate additional CO_2e emissions.

We implemented the MNL using the "nnet" package in R to derive the probabilities of parcel locker delivery. All subsequent computations were conducted in Python following Algorithm 1. We performed the analyses on a Windows computer with 8 GB memory and a 2.6 GHz Intel Core i5 processor.

4.2 Base case

In the base case, we investigate the impact of MPLs on LMD networks for each city. Since the data are from 2019, we use a CO_2e price of 25 euros per ton (ECB, 2020). In addition, we set the service time at MPL stops to 6 hours to allow recipients sufficient pick-up time, and use a drop factor of 13 parcels per stop in accordance with our undisclosed industry partner. Since MPLs are likely to drive autonomously in the future, we set τ to 0, indicating that no personnel are required to observe MPLs while driving. However, in Section 4.3, we show the impact if human intervention is necessary.

Table 3 provides an overview of the results for all regional clusters and cities. We present LMD network configurations for home and SPL delivery, and for LMD networks including MPL delivery. In this manner, the additional effect of MPLs can be highlighted.

Table 1. Selected cities per regional cluster

Population	City selection
> 500,000	A, B, C
100,001–500,000	D, E
50,001–100,000	F, G
20,001–50,000	H, I
10,001–20,000	J, K
5,000–10,000	L, M
< 5,000	N, O

Source(s): Peppel and Spinler (2022)

Table 2. City characteristics

City	Population density*	Demand point density*			Shipment density*		
		25% quartile	Mean	75% quartile	25% quartile	Mean	75% quartile
A	2,438	3	20	105	8	61	358
B	4,777	3	59	180	7	217	815
C	3,074	2	11	109	5	32	380
D	1,039	2	8	56	5	27	164
E	2,236	3	13	105	10	46	443
F	653	3	11	35	9	31	99
G	733	3	9	30	7	32	79
H	565	1	10	40	3	25	116
I	539	2	12	32	6	27	98
J	134	1	4	9	4	11	27
K	663	1	5	25	3	16	72
L	177	1	2	43	2	4	16
M	194	1	3	24	3	9	60
N	47	1	3	6	1	8	21
O	48	1	4	5	2	7	11

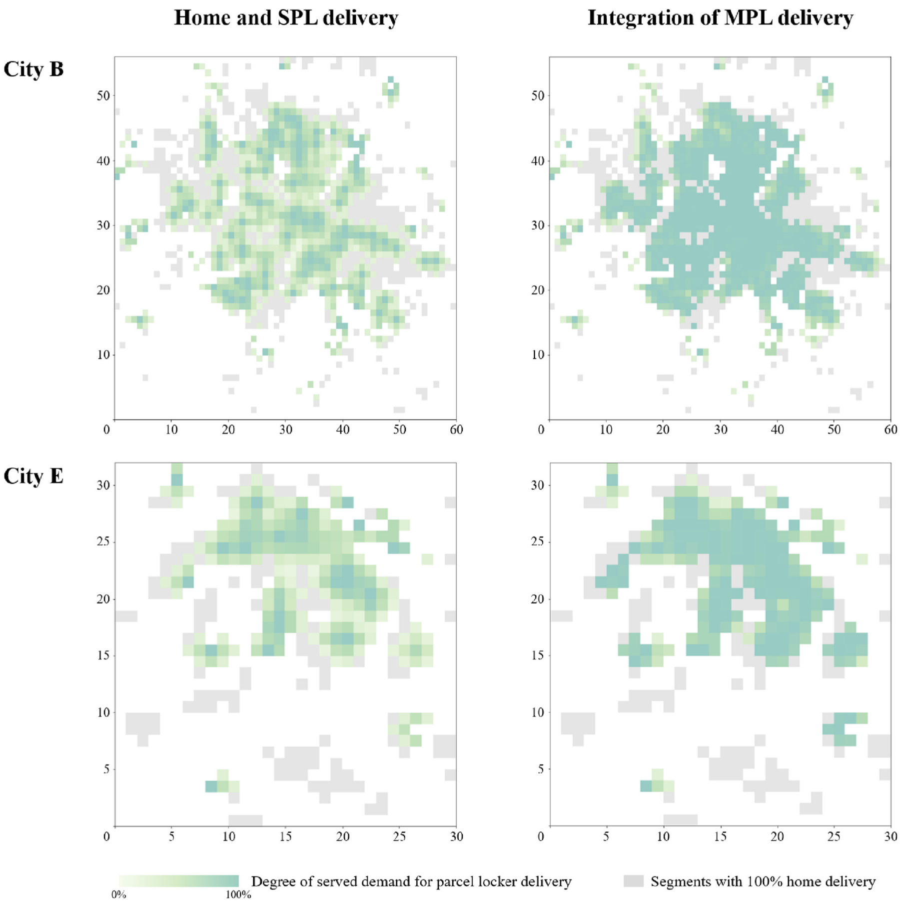
Note(s): *per square kilometer
Source(s): Peppel and Spinler (2022)

Table 3.
Base case results

		Home and SPL delivery						Home, SPL, and MPL delivery								
Population	City	Home	SPL	Cost savings	CO_2e savings	CO_2e LSP	Served PL demand	Home	SPL	MPL	Activated MPLs	Cost savings	CO_2e savings	CO_2e LSP	Served PL demand	MPL utilization
> 500,000	A	81%	19%	5.0%	−0.9%	3.5%	51%	64%	19%	17%	178/389	13.3%	8.4%	16.6%	96%	35%
	B	79%	21%	8.7%	−0.6%	4.8%	65%	68%	21%	11%	102/247	14.2%	5.8%	13.9%	98%	34%
	C	74%	26%	8.0%	−1.6%	4.4%	62%	60%	26%	14%	63/233	15.2%	6.1%	15.5%	97%	34%
100,001–500,000	D	80%	20%	9.1%	−7.4%	3.8%	68%	71%	20%	9%	19/62	12.4%	−6.3%	9.5%	97%	29%
	E	68%	32%	14.1%	−3.3%	6.8%	66%	54%	32%	14%	19/57	22.8%	2.1%	16.7%	95%	42%
50,001–100,000	F	83%	17%	3.8%	−13.9%	−4.2%	83%	81%	17%	2%	1/25	4.0%	−14.5%	−3.6%	92%	18%
	G	89%	11%	3.2%	−3.5%	1.0%	49%	81%	11%	8%	3/19	5.8%	−3.5%	4.4%	86%	27%
20,001–50,000	H	78%	22%	8.6%	−7.4%	3.8%	73%	73%	22%	5%	2/17	9.7%	−8.5%	5.2%	90%	20%
	I	86%	14%	3.7%	−7.2%	2.1%	76%	86%	14%	0%	0/9	–	–	–	–	–
10,001–20,000	J	82%	18%	−0.7%	−7.0%	−0.7%	72%	82%	18%	0%	0/3	–	–	–	–	–
	K	88%	12%	−6.7%	−7.7%	−4.1%	50%	79%	12%	9%	1/11	−4.7%	−10.3%	−4.1%	86%	16%
5,000–10,000	L	88%	12%	−7.7%	−3.0%	−1.3%	59%	88%	12%	0%	0/3	–	–	–	–	–
	M	87%	13%	−3.4%	−3.2%	−0.7%	50%	87%	13%	0%	0/3	–	–	–	–	–
< 5,000	N	100%	0%	–	–	–	–	100%	0%	0%	0/2	–	–	–	–	–
	O	100%	0%	–	–	–	–	100%	0%	0%	0/0	–	–	–	–	–

Note(s): PL = parcel locker
Source(s): Own illustration

First, we focus on the home and SPL delivery network. In our analysis of the respective proportions of delivery modes, approximately 80% of parcels are shipped via home delivery and 20% via SPL delivery. The percentages for SPL delivery are higher in larger cities and decrease with city size. The highest cost savings of 14.1% are realized in City E. According to our model, for regional clusters below 20,000 inhabitants, SPLs are associated with additional costs. This is mainly due to the higher impact of customer pick-up costs, since recipients in less populous areas tend to use their own cars, emitting CO_2e and driving extra trips more often than recipients in large cities with highly developed public transportation networks. The next two columns present the CO_2e emissions. The first, CO_2e savings, includes CO_2e emissions generated during the LSP's deliveries and customer pick-ups, while the second, CO_2e LSP, focuses only on LSP emissions. From a global perspective, our results indicate that customer pick-ups do less harm to the environment in metropolitan areas than in rural areas owing to different pick-up behavior. From an LSP perspective, SPLs save emissions in most cities. The proportion of fulfilled demand for parcel locker delivery ranges between 49% and 83%, indicating that a substantial proportion of recipients' needs remain unsatisfied, as illustrated on the left-hand side of Figure 3.



Source(s): Own illustration

Figure 3.
Change in satisfied demand for parcel locker delivery: base case

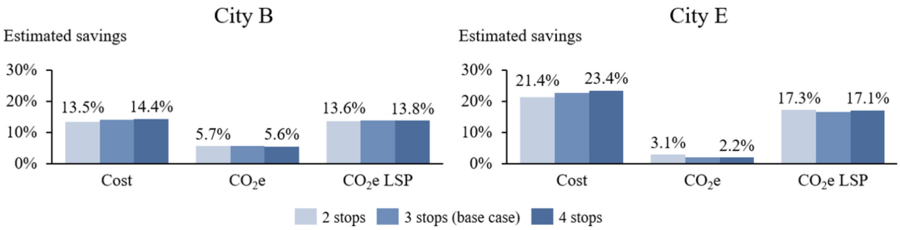
The second part of Table 3, dealing with home, SPL, and MPL delivery, is structured similarly. When MPLs are integrated into the LMD network, they fulfill 2–17% of parcel deliveries. Only particular depots operate MPLs. The results demonstrate that MPLs should be deployed in more populous cities with more than 20,000 inhabitants, where significant cost savings can be made. For instance, the new LMD network yields 13.3% cost savings for City A compared with 5.0% for home and SPL delivery.

In most cases, CO_2e emissions improve in cities with high population densities. In contrast, additional emissions are generated in cities F, H, and K due to different pick-up behaviors that have adverse environmental effects. This effect is demonstrated for City K, where LSPs' CO_2e emissions remain constant while total CO_2e savings, including customer pick-ups, decline. In contrast to home and SPL delivery, the demand for parcel locker delivery can be satisfied to a greater extent with the new LMD setup, with fulfillment ranging between 86% and 98%. Figure 3 illustrates the served demand for parcel locker delivery for the home and SPL delivery case and with the integration of MPL delivery per segment in City B and E. The darker the green color, the higher the degree of served parcel locker demand per segment. Gray segments are served completely by home delivery. The maps of both cities clearly illustrate the benefits of MPLs satisfying client demand. MPLs' utilization also differs across cities, between 16% to 42%.

4.3 Sensitivity analyses

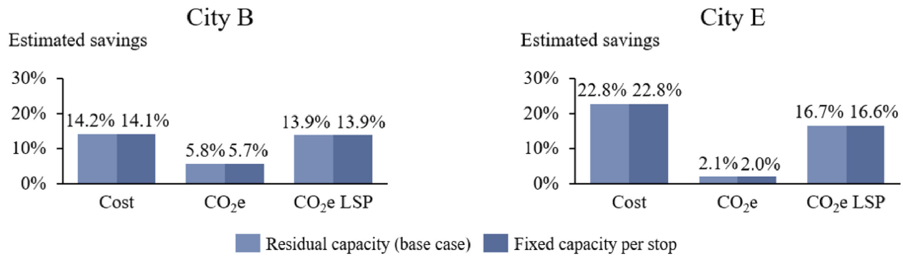
In this section, we present several sensitivity analyses. In the base case, there are three MPL stops. Modifying the service time at MPL stops or the drop factor may yield a different number of stops. We investigate the effect for two and four stops (see Figure 4). In general, more stops deliver higher cost savings, while CO_2e savings vary only marginally. More demand for parcel locker delivery can be satisfied with additional MPLs in the LMD network. Since we assume that recipients pick up their parcels within the designated period, the results must be interpreted with caution. The higher the number of stops, the shorter the time windows for parcel pick-ups, leading to missed parcel pick-ups in real life.

Moreover, in the base case, we allow MPLs to cover recipients' demand up to the maximum MPL capacity at the first stop, leading to no additional MPL stops. In contrast to this flexible approach, we test the effect of capacity reservations per stop, so that for each stop the same number of shipments can be served. In this case, the model yields slightly higher costs and CO_2e emissions, while utilization of MPLs decreases (see Figure 5). This approach has virtually no impact on satisfying demand for parcel locker delivery.



Note(s): City B uses 102 and 105 MPLs, resulting in 96% and 99% satisfied parcel locker demand for two and four stops, while City E deploys 18 and 20 MPLs and yields 92% and 97% satisfied demand for parcel locker delivery, respectively
Source(s): Own illustration

Figure 4. Variation in the number of MPL stops



Note(s): City B uses 105 MPLs resulting in 98% satisfied parcel locker demand and 33% MPL utilization in the restricted case, while City E deploys 20 MPLs and yields 96% satisfied demand for parcel locker delivery with 40% MPL utilization, respectively
Source(s): Own illustration

Figure 5.
Capacity restrictions per MPL stop

For all cities, we determine a fixed pick-up radius. If we reduce the pick-up radius r^{max} by z, cost savings decrease, but additional CO_2e emissions savings can be generated, as shown in Table 4. In this scenario, recipients' travel distances decrease, leading to lower emissions. Less of the demand for parcel locker delivery is satisfied. Reducing the pick-up radius makes use of MPLs more attractive. For example, an additional 25 MPLs would be used in City B. In contrast, increasing the pick-up radius, where customers are willing to travel greater distances, yields higher cost savings at the expense of CO_2e emissions. Fewer MPLs would be used in this case. Since the previous scenario reflects recipients' desire for shorter travel distances (Iwan *et al.*, 2016; Lemke *et al.*, 2016), it is considered to describe potential future changes more realistically.

In the current LMD sector, LSPs and SPL operators have announced increases to their SPL networks (DHL, 2021a). To account for this trend, we investigate the impact of changing the SPL capacity of the LMD network. If the capacity is increased by 50%, up to 8% additional demand for parcel locker delivery can be fulfilled by SPLs, while fewer MPLs are required (Table 5). However, MPLs are replenished at the depot, which brings cost advantages with regard to home delivery. When the number of MPLs in the LMD network decreases, fewer cost savings can be realized.

Moreover, recipients may become more comfortable with using parcel lockers in the future. Thus, we investigate the effect of increased SPL usage, leading to higher utilization of

		Home and SPL delivery				Home, SPL, and MPL delivery					
City	Case	Cost savings	CO_2e savings	CO_2e LSP	Served PL demand	Activated MPLs	Cost savings	CO_2e savings	CO_2e LSP	Served PL demand	MPL utilization
B	-z	5.4%	1.0%	3.8%	50%	127/247	13.7%	11.5%	16.8%	95%	38%
	Base	8.7%	−0.6%	4.8%	65%	102/247	14.2%	5.8%	13.9%	98%	34%
	+z	10.5%	−3.2%	4.9%	73%	86/247	14.4%	1.0%	11.9%	98%	32%
E	-z	9.9%	0.2%	5.5%	53%	27/57	21.8%	12.1%	21.7%	94%	42%
	Base	14.1%	−3.3%	6.8%	66%	19/57	22.8%	2.1%	16.7%	95%	42%
	+z	16.1%	−7.5%	7.1%	72%	17/57	23.6%	−5.1%	14.8%	97%	41%

Note(s): PL = parcel locker
Source(s): Own illustration

Table 4.
Sensitivity analysis: variation in pick-up radius

City	Case	Home and SPL delivery: Cost savings	CO_2e savings	CO_2e LSP	Served PL demand	Home, SPL, and MPL delivery: Activated MPLs	Cost savings	CO_2e savings	CO_2e LSP	Served PL demand	MPL utilization
B	−50%	6.3%	−1.0%	2.4%	41%	132/247	17.8%	10.5%	18.6%	97%	46%
	−25%	8.1%	−0.8%	3.9%	56%	117/247	15.7%	7.6%	15.7%	98%	38%
	Base	8.7%	−0.6%	4.8%	65%	102/247	14.2%	5.8%	13.9%	98%	34%
	+25%	8.2%	−0.6%	5.2%	69%	96/247	12.6%	4.9%	13.0%	98%	32%
	+50%	7.3%	−0.5%	5.4%	72%	91/247	11.2%	4.5%	12.6%	97%	31%
E	−50%	8.4%	−2.8%	2.8%	37%	27/57	27.9%	10.0%	24.5%	95%	58%
	−25%	12.0%	−3.1%	5.1%	54%	24/57	25.2%	5.5%	20.2%	96%	48%
	Base	14.1%	−3.3%	6.8%	66%	19/57	22.8%	2.1%	16.7%	95%	42%
	+25%	14.3%	−3.4%	7.6%	72%	17/57	20.9%	0.5%	15.2%	96%	38%
	+50%	13.4%	−3.4%	8.0%	74%	16/57	19.1%	−0.2%	14.5%	95%	36%

Note(s): PL = parcel locker
Source(s): Own illustration

Table 5. Sensitivity analysis: variation in SPL capacity

SPLs. This results in more compartments of SPLs being occupied, reducing the opportunity to receive parcels at SPLs (see Table 6). Consequently, MPLs become more attractive and are increasingly used. Total cost savings in the LMD network increase by up to 1.5% compared with the base case, due to the eco-friendliness of MPLs. CO_2e savings may amount to 9.7%.

Since investing in a new technology such as MPLs entails risk, LSPs may wish to invest in only a limited number of MPLs. Hence, we test several thresholds of shipments per square kilometer as a heuristic for deploying MPLs at depots. Together with our industry partner, we determined that 100 shipments per square kilometer would be the best performing threshold. This approach requires about half as many MPLs as in the base case, reducing the organizational effort required to introduce MPLs into an LMD network. The results in Table 7 reveal that cost savings decrease slightly, by 0.1% for City B and by 3.1% for City E. The satisfied demand for parcel locker delivery shrinks by up to 13%, while the MPL utilization is up to 22% higher (City E). We clearly see that introducing the first MPLs into the LMD

City	Case	Home and SPL delivery: Cost savings	CO_2e savings	CO_2e LSP	Served PL demand	Home, SPL, and MPL delivery: Activated MPLs	Cost savings	CO_2e savings	CO_2e LSP	Served PL demand	MPL utilization
B	30% (Base)	8.7%	−0.6%	4.8%	65%	102/247	14.2%	5.8%	13.9%	98%	34%
	40%	7.7%	−0.7%	4.3%	61%	111/247	14.2%	6.7%	14.8%	98%	36%
	50%	6.4%	−0.8%	3.7%	54%	123/247	14.3%	7.9%	16.1%	98%	38%
	60%	4.5%	−1.0%	2.9%	46%	128/247	14.8%	9.7%	17.8%	98%	43%
E	30% (Base)	14.1%	−3.3%	6.8%	66%	19/57	22.8%	2.1%	16.7%	95%	42%
	40%	12.3%	−3.2%	6.0%	60%	21/57	23.2%	3.6%	18.3%	95%	46%
	50%	9.6%	−3.1%	4.8%	51%	24/57	23.7%	6.2%	20.9%	96%	50%
	60%	6.6%	−2.9%	3.5%	42%	26/57	24.3%	8.7%	23.4%	95%	56%

Note(s): PL = parcel locker
Source(s): Own illustration

Table 6. Sensitivity analysis: variation in SPL utilization

network may generate substantial savings, while the effect flattens with higher numbers of MPLs.

During the initiation phase of MPLs, human intervention may be necessary to control them in difficult situations, similar to drone operations. This means that humans are located at a central location to observe MPLs while driving. They are able to intervene remotely by driving MPLs manually if necessary. Furthermore, autonomous driving may be subject to local regulations and is often allowed only in specific areas. Sometimes operating personnel are required to control the devices. Thus, we evaluate the impact of human intervention by varying τ as the number of required personnel observing MPL tours while MPLs are driving. The results show that even in the initiation phase, when two operators may be required to control an MPL, up to 15.2% of cost savings (Table 8) and substantial emissions savings may be realized in the home and SPL delivery network.

4.4 Growth case

The e-commerce sector is expected to continue to grow, leading to more parcel shipments (Janjevic and Winkenbach, 2020; Statista, 2020b). For this reason, we construct a growth case with the following assumptions. Since battery technology has evolved in recent years and governments are providing various subsidies for eco-friendly transportation, we assume that the share of BEVs will increase further (Li *et al.*, 2021b). LSPs' fleets will convert towards 75% BEVs as targeted by our industry partner, while the proportion of BEVs in private fleets will increase to 5%.

		Home, SPL, and MPL delivery					
City	Case	Activated MPLs	Cost savings	CO_2e savings	CO_2e LSP	Served PL demand	MPL utilization
B	Base	102/247	14.2%	5.8%	13.9%	98%	34%
	Threshold	53/247	14.1%	4.7%	12.2%	90%	51%
E	Base	19/57	22.8%	2.1%	16.7%	95%	42%
	Threshold	7/57	19.7%	0.9%	13.5%	82%	64%

Note(s): PL = parcel locker
Source(s): Own illustration

Table 7.
Sensitivity analysis: density threshold

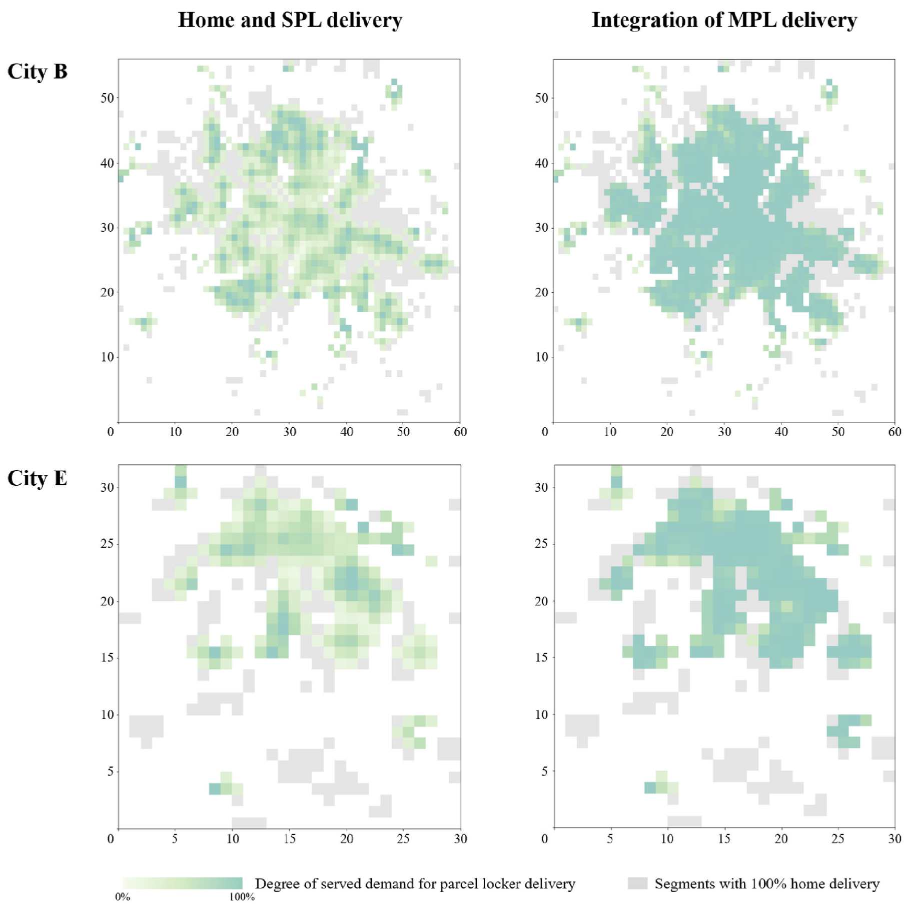
		Home, SPL, and MPL delivery					
City	τ	Activated MPLs	Cost savings	CO_2e savings	CO_2e LSP	Served PL demand	MPL utilization
B	0 (Base)	102/247	14.2%	5.8%	13.9%	98%	34%
	0.5	69/247	12.4%	5.6%	13.6%	96%	48%
	1.0	49/247	11.4%	5.2%	12.9%	93%	61%
	1.5	38/247	10.5%	4.7%	12.2%	90%	72%
	2.0	28/247	10.1%	4.1%	11.3%	87%	85%
E	0 (Base)	19/57	22.8%	2.1%	16.7%	95%	42%
	0.5	11/57	20.3%	2.8%	16.8%	91%	63%
	1.0	10/57	17.9%	2.8%	16.5%	90%	65%
	1.5	7/57	16.6%	1.8%	14.9%	86%	77%
	2.0	2/57	15.2%	−1.4%	9.8%	73%	100%

Note(s): PL = parcel locker
Source(s): Own illustration

Table 8.
Sensitivity analysis: human intervention

CO_2e emission costs are expected to double (Bundesregierung, 2019). We consider a five-year time horizon with 5% annual growth in shipment volumes (Statista, 2019), meaning that parcel volumes will increase by +27.6%, which we define as the medium-growth case. In addition, we build low- and high-growth cases deviating by 25% from the medium-growth case. Since the COVID-19 pandemic has accelerated the growth in e-commerce, we also create an extreme-growth case with +50%.

The growth case illustrates that existing SPLs cannot maintain their levels of demand satisfaction for parcel locker delivery in the home and SPL network, leading to lower cost savings than in the base case (see Figure 6 compared with Figure 3). In Figure 6, the home and SPL delivery case reveals less dark green segments than in the base case indicating lower degrees of served demand for parcel locker delivery. By adding MPLs to the network, the percentage of satisfied demand for parcel locker delivery increases as indicated by a high level of dark green segments. In addition, even more cost savings can be realized (Table 9), as MPLs are able to compensate for the demand surplus when deployed across a city, and their utilization increases accordingly. Furthermore, since the LSP fleet will become more sustainable in combination with the environmentally-friendly MPL fleet, recipient pick-ups



Source(s): Own illustration

Figure 6.
Change in satisfied demand for parcel locker delivery: growth case

City	Case	Home and SPL delivery: Cost savings	CO_2e savings	CO_2e LSP	Served PL demand	Home, SPL, and MPL delivery: Activated MPLs	Cost savings	CO_2e savings	CO_2e LSP	Served PL demand	MPL utilization
B	Base	8.7%	−0.6%	4.8%	65%	102/247	14.2%	5.8%	13.9%	98%	34%
	+20.7% (low)	8.5%	−2.4%	2.7%	60%	122/247	16.0%	5.5%	13.8%	98%	41%
	+27.6% (medium)	8.4%	−2.2%	2.7%	58%	127/247	16.5%	6.1%	14.5%	98%	44%
	+34.5% (high)	8.2%	−2.1%	2.7%	56%	137/247	16.9%	6.7%	15.2%	98%	45%
	+50.0% (extreme)	7.8%	−1.8%	2.7%	52%	133/247	18.0%	7.7%	16.1%	97%	54%
E	Base	14.1%	−3.3%	6.8%	66%	19/57	22.8%	2.1%	16.7%	95%	42%
	+20.7% (low)	13.1%	−5.2%	4.2%	58%	27/57	25.2%	3.0%	18.5%	97%	47%
	+27.6% (medium)	12.6%	−4.9%	4.1%	56%	28/57	25.9%	4.1%	19.7%	97%	51%
	+34.5% (high)	12.1%	−4.7%	4.0%	53%	30/57	26.6%	5.0%	20.7%	97%	53%
	+50.0% (extreme)	11.1%	−4.2%	3.8%	48%	33/57	27.9%	7.3%	23.2%	97%	60%

Note(s): PL = parcel locker
Source(s): Own illustration

Table 9.
Growth case results

will only partially impair the positive effect on CO_2e emissions, although private fleets will transform more slowly.

4.5 Discussion

Our results show that MPLs are a suitable technology to attract users. The case study results demonstrate that MPLs may yield additional cost savings of up to 8.7% and CO_2e extra emission savings of 5.4%, addressing our first research question.

However, the effects differ between the regions investigated, with cities ranging from less than 5,000 to more than 500,000 inhabitants. Although introducing MPLs into LMD networks produces cost savings for all eligible cities (i.e. cities A-H and K), CO_2e emissions may also increase, as in cities F, H, and K. In less populous areas, recipients tend to take additional trips for pick-ups, generating additional CO_2e emissions. In contrast, recipients in larger cities choose more environmentally-friendly means of transportation and combine trips. Thus, a certain population density threshold is required for MPLs to yield benefits, balancing cost-saving effects and potential additional emissions. For instance, cost savings can be realized in City F while additional CO_2e emissions are limited. In answer to our second research question, we recommend that MPLs should be deployed in cities with more than 20,000 inhabitants.

Our growth scenario demonstrates that existing SPL networks will be less able to satisfy demand for parcel locker deliveries. Cost savings in the home delivery and SPL delivery network will decrease. Introducing MPLs into the network will impact positively by increasing satisfied demand for parcel locker delivery to about 98%. Furthermore, cost savings can be increased substantially, by up to 27.9%. Hence, MPLs can account for demand growth and fluctuating demand across the city, addressing our third research question.

4.6 Managerial implications

Travel distances to parcel lockers are a crucial criterion to encourage recipients to use them (Iwan *et al.*, 2016; Lemke *et al.*, 2016). Our findings demonstrate potential savings for LSPs and benefits for recipients of introducing MPLs into LMD networks. We identify five key managerial implications for LSPs.

First, MPLs should be operated with a few stops (e.g., three) per day, rather than visiting recipients individually, one by one in imitation of home delivery. Our suggested operating model enables customers to collect parcels at their convenience within a reasonable time frame. The alternative option would result in similar not-at-home problems to home delivery.

Second, MPLs should be deployed in regions with more than 20,000 inhabitants. Our study shows that these areas yield considerable cost savings due to higher population density. However, less populous cities may become attractive in the future. Furthermore, LSPs should test MPLs for robustness, maintenance requirements, and undesired interactions with pedestrians, such as vandalism.

Third, MPLs' utilization could still be improved. We suggest that managers should also use MPLs to address the first mile for customers sending parcels or returning goods (Bergmann *et al.*, 2020). However, the number of compartments should not be reduced, since the growth case illustrates the speed with which utilization of MPLs may increase.

Fourth, hesitant LSPs should conduct field tests in regions similar to City E, and apply our suggested density threshold as a criterion for installing MPLs. In this case, only seven MPLs would be required to test whether the estimated cost savings could be realized in practice.

Fifth, since MPLs will be closer to recipients' homes, new users may be attracted who were previously hesitant. This would also make expansion of the current SPL network more attractive with the introduction of new SPL locations. In this case, MPLs could be used during the transformation phase.

In conclusion, we highly recommend that LSPs should integrate MPLs into their delivery networks. MPLs offer an opportunity to cope with fluctuating demand for parcel locker delivery across cities, while generating cost and CO_2e savings. They should thus be regarded as a complementary technology, as Peppel *et al.* (2022) propose, to address recipients' demand and improve customer satisfaction.

5. Conclusion

The boom in e-commerce has resulted in increased shipment volumes. New technologies such as MPLs may help to mitigate the challenges associated with this trend. This study investigates the impact of MPL solutions on the LMD network from economic and environmental perspectives. To account for discrete consumer behavior, we formulate an MNL model based on recipients' travel distance to parcel lockers and availability at home. We build a mathematical model with binary decision variables to determine near-optimal MPL stop locations that reduce total costs and CO_2e emissions in the LMD network. Our study reveals that MPLs can yield additional cost savings of up to 8.7% and extra CO_2e savings of up to 5.4% for LMD networks, including home and SPL delivery.

Our analysis of 15 cities across different regions demonstrates that MPLs should be installed in more populous cities with at least 20,000 inhabitants, since MPLs require a specific population density to yield positive cost effects. In addition, recipient pick-ups have adverse environmental effects owing to the large number of extra trips that emit CO_2e. Furthermore, our various sensitivity analyses and growth case demonstrate the benefits of MPLs, which can address demand for parcel locker delivery more flexibly while producing cost and emissions savings. The existing SPL network will be able to cover rising demand to only a limited extent. We provide managerial guidance for LSPs extending their LMD networks with MPLs in relation to operational setups, suitable regional clusters, and implementation strategies.

Amongst several opportunities for further research, future studies might investigate operations in more detail. In our case, we assume that MPLs always start and end their tours at the same depot. Researchers might also examine tours with varying start- and end-points to increase flexibility, which would require multiple MPLs to be serviced per depot. Furthermore, MPLs might operate several tours per day, for example in highly frequented areas. Future studies might explore the effect of replenishing MPLs during active tours to avoid having to return to depots, and future analysis might also highlight the impact of MPLs in smoothing demand peaks at Christmas and during similar events. In addition, the service time per stop affects the utility using parcel locker services. Thus, further studies can integrate service time per stop as an internal model parameter. Additional studies should investigate recipients' willingness to use MPLs vis-à-vis SPLs in detail and also cover social dimensions to improve the MNL. Finally, we suggest that researchers should include dynamic data that consider changing recipients' locations to replicate real-life more accurately.

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(The Appendix follows overleaf)

Appendix
Notation

Sets		
C	set of delivery options: parcel locker delivery p and home delivery h	
I	set of customer segments: i = 1, . . ., maximum number of segments	
N	set of recipients: n = 1, . . ., maximum number of recipients	
Parameters		
e_{hn}	stochastic component as a random error term for recipient n favoring home delivery h	[]
e_{pn}	stochastic component as a random error term for recipient n favoring parcel locker delivery p	[]
P_{hn}	probability of choosing home delivery h for recipient n	[%]
P_{pn}	probability of choosing parcel locker delivery p for recipient n	[%]
U_{hn}	utility of an individual recipient n choosing option home delivery h	[]
U_{pn}	utility of an individual recipient n choosing option parcel locker delivery p	[]
V_{hn}	deterministic component of utility as a function of travel distance and availability at home for home delivery h of recipient n	[]
V_{pn}	deterministic component of utility as a function of travel distance and availability at home for parcel locker delivery p of recipient n	[]
λ_i	proportion of recipients in segment i favoring home delivery	[%]
ϕ_{ih}	aggregation of recipients in segment i choosing home delivery h	[]
ϕ_{ip}	aggregation of recipients in segment i choosing parcel locker delivery p	[]
ω_i	proportion of recipients in segment i favoring parcel locker delivery	[%]

Table A1.
Notation for MNL model

Parameters		
c^e	energy cost factor	[Euro/kWh]
c^d	operating cost during driving of an MPL	[Euro/h]
c^h	personnel cost factor	[Euro/h]
C_j^M	maximum number of free compartments of MPL associated with depot j	[]
c^p	operating costs of MPL at pick-up location	[Euro/h]
c^r	replenishment costs of the MPL at the depot	[Euro]
e^c	energy consumption	[kW]
f_j	total daily cost of operations to serve city segments by depot j with an MPL	[Euro]
f^n	fixed MPL costs per day, including maintenance and rent for stop locations	[Euro]
n_j	number of stops an MPL from depot j can serve on a single route	[]
t^a	service time per stop	[h]
t^d	inter-stop travel time	[h]
$T^{\max}$	maximum service time	[h]
t^s	setup time per tour, e.g., charging of MPL	[h]
v	average velocity of MPL	[km/h]
γ	density of MPL stops	[]
δ_j	average number of stops a single MPL associated with depot j can serve in $T^{\max}$	[h]
κ	circuity factor	[]
ρ	average number of delivery items	[]
ξ_j	effective carrying capacity of an MPL associated with depot j in terms of stops that could be served	[]
τ	required personnel observing MPL tours while driving	[]

Table A2.
Additional notation for routing cost estimation

Sets		
I	set of customer segments: i = 1, . . ., maximum number of segments	
J	set of depot locations	
K	subset of segments which are candidates to be served by parcel locker delivery, $K \subseteq I$	
L	subset of segments for candidate MPL stops, $L \subseteq I$	
X	set of SPL locations	
Parameters		
a	calibration factor for surcharge factors	[]
$C_i^{M,R}$	residual number of free compartments of MPL located in segment i	[]
C_i^S	maximum number of free compartments of SPL located in segment i	[]
d^a	average pick-up distance	[km]
d_{ik}	layer based on distance between center segment i and candidate segment k	[]
e^{Hmax}	maximum surcharge factor for emission costs	[Euro]
e^r	recipient's emission cost factor for parcel pick-up	[Euro/km]
e^o	emission cost of an SPL during operation	[Euro]
e^H	emission cost factor per parcel for home delivery	[Euro]
e_i^H	emission cost factor per parcel for home delivery in segment i	[Euro]
e_k^S	emission cost factor per parcel for SPL delivery in segment k	[Euro]
f^S	fixed setup cost of an SPL	[Euro]
g_k	proportion of recipients generating additional CO_2e during pick-up at parcel lockers in segment k	[%]
K^H	costs for home delivery	[Euro]
K^M	costs for MPL delivery	[Euro]
K^S	costs for SPL delivery	[Euro]
K^T	total costs for delivery network	[Euro]
o^S	daily operating costs of an SPL	[Euro]
$r^{\max}$	maximum radius of a parcel locker's catchment area	[km]
s^{Hmax}	maximum surcharge factor for shipping costs	[Euro]
s^H	shipping costs per parcel for home delivery	[Euro]
s_i^H	shipping costs s^H per parcel for home delivery in segment i	[Euro]
s_k^S	shipping costs s^S per parcel for SPL delivery in segment k	[Euro]
V_i	total demand for parcel delivery in segment i	[]
V_i^H	volume of parcel shipments to homes in segment i	[]
V_l^M	volume of parcel shipments to MPL stop in segment l	[]
V_k^S	volume of parcel shipments to SPLs in segment k	[]
x_i	pre-determined SPL locations as a set of binary variables x_i, $i \in I$, 1 if an SPL is located at segment i and 0 otherwise	[]
z	edge length of segments	[km]
ϵ_{ik}	distance parameter to adjust probabilities of using SPL or MPL of segment i in segment k	[%]
μ_k	proportion of recipients in segment k already served by an SPL	[%]
η	slope of the decay function	[]
Decision variable		
$y_{l,j}$	1 if an MPL associated with depot j stops at segment l and 0 otherwise	

Table A3. Additional notation for mixed-integer linear programming model

Corresponding author
Marcel Peppel can be contacted at: marcel.peppel@whu.edu