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Parcel lockers vs home delivery: a model to compare last-mile delivery cost in urban and rural areas

Abstract

Purpose – This paper investigates the economic performances of two B2C e-commerce last-mile delivery options – namely Parcel Lockers (PLs) and traditional Home Delivery (HD) in contexts where e-commerce is still at its early stages. It analyses and compares two different implementation contexts, i.e. urban and rural areas.

Design/methodology/approach– This study develops an analytical model that estimates delivery costs for both the PL and HD options. The model is applied to two base cases (representative of urban and rural areas in Italy) and sensitivity analyses are subsequently performed on a set of key variables/parameters (i.e. PL density, PL fill rate and PL annual costs). To support the model development and application, interviews with practitioners were performed.

Findings – PLs imply lower delivery cost than HD, independently from the implementation area (urban or rural): advantages mainly derive from the higher delivery density and the drastic reduction of failed deliveries. Benefits entailed by PLs are more significant in rural areas due to lower PL investments and annual costs, as well as higher HD costs.

Originality – This paper offers insights to both academics and practitioners. On the academic side, it develops a model to compare the delivery cost of PL and HD, which includes the analysis of urban and rural contexts. This could serve as a platform for developing/informing future analytical/optimisation contributions. On the managerial side, it may support practitioners in making decisions about the implementation of PLs and HD, to benchmark their costs and to identify the main variables and parameters at play.

Keywords: B2C e-commerce, last-mile delivery, parcel lockers, innovation

Introduction

Business to Consumer (B2C) e-commerce is growing in many countries and across different industries. Online sales pose several new logistics challenges to companies, and one of the most critical is the management of the last-mile delivery – i.e., the last leg of the delivery, to the customer's home or a collection station (Gevaers et al., 2014). Last-mile logistics is crucial for both its effects on the service level (Vakulenko et al., 2018) and its significant contribution to logistics costs (Vanelslander et al., 2013).

Among the "innovative" last-mile delivery solutions proposed to overcome such issues, an interesting option is represented by Parcel Lockers (PLs). PLs are boxes used by different customers, aggregated into structures typically located in public places (e.g., supermarkets or stations) (McKinnon and Tallam, 2003). PLs seem to represent a very promising alternative to traditional Home Delivery (HD), as they are easily accessible by customers at their convenience (Vakulenko et al., 2018), they allow to increase the delivery density (Deutsch and Golany, 2018) and they drastically reduce the probability of incurring in failed deliveries (Wang et al., 2018). Accordingly, both academics (Mangiaracina et al., 2019) and managers (Ranieri et al., 2018) have been expressing interest in better understanding the impact that PL delivery has if compared to HD, especially from an economic perspective.

Extant works estimating PLs delivery costs are characterised by different weaknesses, which this research aims to overcome. Among them, first and foremost they do not analyse all the costs entailed by PL deliveries; as a result, the outcomes of the various works are not aligned among each other, and rely on partial assumptions that may lead to incorrect conclusions. Moreover, previous studies typically do not include neither investments nor a medium-term economic view, thus not considering how the benefits entailed by PLs allow to repay such investments. On the contrary, this contribution aims to compare the pure PL and HD options from a more comprehensive perspective (including all the costs – i.e., transport costs, operating costs and failed delivery costs – but also the associated investments). Second, previous literature focusses on cities only, without investigating rural contexts (despite the interest customers have been showing towards these areas (Lachapelle et al., 2018)). The present work develops instead a model that suits both urban and rural areas and applies it to both contexts, considering all the relevant different elements between the two (e.g., delivery density, travel speed of the van, cost for renting the land). Third, extant papers comparing the delivery cost of PLs and HD rely on a delivery process modelling that is not well representative of real ones. Conversely, this research introduces a more realistic configuration (characterised by: different attempts considered for each parcel, “traditional” HD with no appointments, the inclusion of the duration of the shift of the driver in the cost function).

These being the premises, the present paper develops – and applies – an analytical model to compare the delivery cost of traditional HD and of deliveries through PLs, comparing two different implementation contexts, i.e., urban and rural areas, overcoming the main shortcomings of existing contributions in the same field.

The remainder of this paper is organised as follows: the second section presents the results of the literature review; the third section formulates the research questions and describes the adopted methodologies; the fourth and fifth sections illustrate the model and its application; the last section summarises the conclusions stemming from the work.

Literature review

In their review of innovative last-mile delivery solutions, Mangiaracina et al. (2019) highlight the need to investigate the savings PLs may entail compared to HD, in order to inform managerial decisions and promote their adoption. More recently, Van Duin et al. (2020) claimed that, when addressing last-mile delivery costs, "scientific literature on parcel lockers is rather scarce".

Table 1 collects the main academic works studying PL deliveries. In particular, it displays the goal of the works, the considered delivery method(s) and the type of costs included in the economic analyses. These costs are: transport cost (from the last courier hub to the final customer); operating cost (e.g., electric consumption, land occupation, maintenance, management); opening cost (investments for purchase and installation); failed delivery cost (to manage failed deliveries when the customer is absent). Two main messages emerge from this comprehensive analysis.

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First, based on their goal, papers may be grouped in two clusters. The first – and more populated – one is devoted to solving the PLs distribution network design problem, i.e., finding the number/location of lockers to serve customers in a defined area, or to defining and solving the associated VRPs. In this case, despite costs are modelled as a part of the objective function, the economic evaluation of PLs is not the goal of the study, and only partial considerations/element may be derived. The second cluster of works aims instead to investigate the impact that implementing PLs as an alternative to traditional HD may have on delivery costs (thus attempting to answer the call for works made by Mangiaracina et al. (2019) and Van Duin et al. (2020)). The four papers belonging to this second cluster are highlighted in grey color.

The second message concerns instead the considered cost: no articles (from any of the two clusters) address all the costs actually faced by logistics players. Although the convenience of PLs has already been investigated in some research efforts, the lack of consideration of relevant cost factors may have led to only partially correct conclusions. As a matter of fact, neglecting some costs entailed by PL may imply underestimating the cost associated to PL, thus overestimating the advantage compared to HD. Hence, there is a need to evaluate if, and to what extent, PL are still convenient, even when assuming a comprehensive perspective and considering all the identified costs.

Table 2 presents a detailed analysis of the papers from the second cluster, which are more aligned to the scope of the present research. Based on the additional classification axes (compared to those of Table 1), it is possible to identify different gaps.

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(i) **Comparison.** Only some articles compare the costs of PL delivery with those of traditional home delivery; other focus instead on combinations of different solutions. The work by Van Duin et al. (2020) – one of the most comprehensive ones – does not provide a comparison between pure PL delivery and pure HD delivery. The base case is a combination of HD and delivery to Collection Delivery Points (CDP), which is compared to PL delivery and delivery with CDP. Such results do not allow to draw any conclusions about the savings that PL entail compared to HD.

(ii) **Costs and investments evaluation.** Considering costs, as already discussed, no papers consider all the cost factors. Considering investments, all the four contributions attempt to show the savings entailed by PL, but fail to estimate the considerable investment behind their purchase and installation. Logistics service providers do not start benefitting from the implementation of PL immediately, but after a few years, because the investments need to be repaid. Hence, the evaluation of the investment, and accordingly the economic analysis on a longer time horizon (and not only based on a single delivery tour) is an important missing element to support them in their decision making process.

(iii) **Area and considered variations.** The benefits of PLs in terms of delivery cost are typically evaluated focussing on cities (e.g., Amsterdam in Van Duin et al. (2020)). Despite some scholars are evidencing the interest of online shoppers in collecting their parcels in lockers located in rural areas (Lachapelle et al., 2018), the potential efficiency gains stemming in these scenarios have not been investigated yet. Some works analyse the variations of some characteristics of the delivery problem (e.g., the delivery density or the speed of the van), but definitive considerations about the difference between urban and rural areas cannot be drawn. As a matter of fact, these areas differ from various points of view, which should be concurrently considered. Urban areas are more populated, with a higher delivery density (Veenstra et al., 2018). The travelling speed of the mean of transport is typically lower in urban areas, due to more stringent speed limits and different traffic conditions (Seghezzi et al., 2020). The land occupation cost (which is key in determining the cost to run a PL) is much higher in urban areas (Wang et al., 2014). Accordingly, it still remains unclear how, and to what extent, the comparison of the delivery cost of PLs and HD may vary between urban and rural scenarios.

(iv) **Delivery process modelling**. The two most relevant works modelling the cost of PLs and traditional HD are those by Iwan et al. (2016b) and Van Duin et al. (2020). Iwan et al. (2016b) – in collaboration with a Polish logistics provider (Bilik, 2014) – estimate some efficiency-related performances for traditional HD and PLs. They show how PLs allow to increase the delivery density, thus delivering a much higher number of parcels (600 vs. 60 per day), travelling a shorter distance (70 vs 150 km), resulting in a lower fuel consumption (1,050,000 vs. 22,500,000 litres per year, i.e., 0.01 vs. 0.23 litres per parcel). Nonetheless, despite the outcomes are relevant and provide a measure of the related benefits, the model underneath them is not presented, and it is thus not possible neither to understand the logics behind it, nor to apply it to other contexts/enhance it to generate new results. The more recent study by Van Duin et al. (2020) illustrates a model to quantify the delivery cost reduction entailed by PLs if compared to traditional delivery options. The authors rely on a standard transport cost function proposed by Blauwens et al. (2010), which contemplates three cost components: one linearly depending on the time spent, one linearly depending on the travelled distance and an "extra-cost" coefficient, accounting for transhipment operations. The overall outcome of the function is a daily delivery cost, which is computed in four scenarios, stemming from different combinations of three delivery options, i.e., home delivery, delivery in CDP and PL delivery. The application context is the "De Pijp" district, in Amsterdam. The results show that the most convenient alternative including PLs entails a daily cost of €2,704.85, while it is €3,210.49 in the traditional home+retail delivery option. On a yearly basis, this allows to save up to €121,356. Both the discussed contributions model a delivery process that is not well representative of the real ones, especially for HD. More specifically, they present three main limitations:

- Only the 1st-attempt failure is considered for deliveries, but subsequent delivery attempts after a missed delivery are not contemplated. Nonetheless, in reality more attempts are typically made (Song et al., 2009).
- Home deliveries are associated to specific time windows (which in the model by Van Duin et al. (2020) are included by means of the W coefficient). This does not happen in many real cases, where traditional home deliveries are not by-appointment (Mangiaracina et al., 2019).
- The duration of the shift of the driver (which is assumed to last 8.5 hours by Van Duin et al. (2020)) is just considered as a constraint, but not as a cost component: the model only checks if the duration of the delivery tour is lower than the delivery shift. Conversely, the cost component depending on the time spent to perform the deliveries does not consider that the drivers should be paid for the entire duration of the delivery tour, even if he/she spends less time to accomplish the deliveries (Seghezzi and Mangiaracina, 2021).

(v) **Results.** In line with the different considered costs and the partial and contrasting assumptions, the results of the four works in terms of savings entailed by PLs are not aligned. Iwan et al. (2016), based on fuel costs, conclude that PLs can lead to 95% savings (which is a very strong statement). Song et al. (2019) and Redi et al. (2020) estimate a saving of around 70% in delivery costs. Finally, the result of Van Duin et al. (2020) is different too; the best alternative (parcel lockers at 66% and home delivery at 34%) differs from the base case by about 16%. Based on the above, a shared and unambiguous view about the comparison between PLs and HD is missing.

Objectives and methodology

In line with the presented premises, this study aims to propose an analytical model to compare the cost of HD and the delivery through PLs, that overcomes the illustrated gaps. The main characteristics of the present research, in contrast with previous literature, are presented in the last row of Table 2 (highlighted in grey color).

- **Comparison**. In order to answer the call for works launched by logistics scholars operating in the field, the aim is to compare pure HD and PL deliveries (i.e., HD only vs. PL only), and estimate the advantages entailed by the best one.
- **Costs and investments evaluation**. The present research includes all the cost items found in the literature – i.e., transport cost, operating cost (e.g., land occupation, electric consumption, maintenance, management) and failed delivery cost – and also the needed investments. Moreover, it does not address the single-tour delivery cost, but it both estimates the average cost per delivery, and evaluates the economic medium-term perspective (estimating the time needed to repay such investment, and the associated Net Present Value after some years).
- **Area and variations.** The analysis considers both urban and rural environments, and compares the economic advantages stemming from PLs in both cities and the countryside. The considered differences between the two areas include all the relevant elements (e.g., density, travel distance, cost of the land rent).
- **Delivery process modelling**. The modelled delivery process is representative of the real ones, in a threefold direction. (i) First, if a delivery is missed, two additional delivery attempts are considered to be made for the same parcel (before bringing it back to the hub, and appointing the customer for the collection). (ii) Second, the analysed home deliveries are "traditional" ones with no appointments, in which the customer is not assigned a time slot *a priori*. (iii) Third, the duration of the shift of the driver is not only considered as a constraint to test the time feasibility of a delivery route, but it is included in the cost function, knowing that the driver needs to be paid for the whole duration.

Addressing all these issues could allow to gain a shared and unambiguous view about the convenience PL entail if compared to HD.

The following research questions (RQs) are defined:

RQ1 – What is the average cost for a B2C e-commerce delivery performed through PLs in an urban area if compared to traditional HD?

RQ2 – How does this change if considering rural areas?

To reach the aforementioned goals, this study adopts an analytical modelling approach based on two stages. First, it develops a model that estimates the delivery cost for the PL and HD options, in urban and rural contexts. Second, it applies the model to gain the numerical insights needed to answer the RQs. More specifically, the model is initially applied to two base cases in Italy, representative of an urban and rural area respectively. Later, some sensitivity analyses are performed on key variables and parameters to test the robustness of the application, and evaluate the impact of variations in the input values on the estimated performances.

Three additional methods are used to support the model development and application: (i) literature review, to ground the present research in the extant scientific knowledge (in line with recent works about last-mile delivery, e.g., Seghezzi et al., 2020); (ii) analysis of secondary sources, such as logistics practitioners' journals and reports (as suggested by Jick, 1979) and (iii) interviews with four practitioners operating in the business (from express couriers – one general manager and one e-commerce manager – and from online retailers – i.e., a logistics manager and an e-commerce manager), to better understand the relevant variables, collect data and validate results (similarly to Giuffrida et al., 2019).

More specifically, two rounds of interviews were performed. First, during the model development, to identify the key variables/parameters, their relations, the main costs. These interviews were semi-structured, to capture ideas and data not previously identified by the authors (Harrell and Bradley, 2009). Second, during the model application, to find reliable data to feed it, as suggested by Mohrman and Lawler (2012). These data collection interviews were supported by checklists reporting all the main variables/parameters for which numerical values were needed (Nutting et al., 2002). To conclude, a final workshop was organised with the same practitioners, to discuss and validate the results of the research (Harland et al., 2019).

The adopted methodology was defined based on both methodological papers in operations management and previous contributions addressing last-mile deliveries.

Concerning the methodological references, according to Bertrand and Fransoo (2002) empirically grounding analytical research in operations management is key "to ensure that there is a model fit between reality and the model"; accordingly, our model was developed and applied in close collaboration with the managerial community. Reiner (2005) highlights the importance of using "quantitative model-driven empirical research" when analysing "industrial systems" (developing an analytical model and applying it to real-life data collected through interviews with practitioners). This process is suitable for contexts where actual results are not available/difficult to collect, as it happens with innovative last-mile delivery solutions, often applied to small extents (Kunešová and Eger, 2017).

Concerning former works about last-mile delivery taken as reference, they mainly pertain to two choices. First, the analytical model follows a “block” architecture – detailed in the “Model” section and based on input variables, context data, output and the algorithm – which is used in different contributions investigating the economic effects of innovative last-mile delivery solutions (e.g., Siragusa et al. (2020), Seghezzi and Mangiaracina (2021)). The definition of these “blocks” helps in distinguishing the “decision” variables from the parameters describing the implementation context, providing a clear structure of the problem and the related data. Second, the developed model is applied to a representative “base case”, and sensitivity analyses are subsequently run on key variables and parameters. This approach is followed by different contributions focussing on last-mile delivery innovation (e.g., Pinto et al. (2019), in evaluating network configurations for drone-delivery; Seghezzi et al. (2020) in the cost analysis for crowdsourcing logistics).

Model

In modelling the last-mile delivery process in the HD and PL cases, delivery tours are dedicated to either HD only or PL only (mixed tours are not contemplated in this work). Moreover, only pure shipment activities from the last hub to the destination have been considered. Both these choices are aligned to the literature in the field. On the one hand, academic works comparing the performances of an innovative delivery solution with the traditional HD usually consider the two options separately (e.g., Wang et al., 2014). On the other hand, the performances of two logistics processes are typically compared from their point of divergence (Edwards *et al.*, 2011), i.e. from where they start to differ (which in this case is the last hub of the courier).

Model architecture

Figure 1 shows the model architecture, consisting of four main building blocks.

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The algorithm, based on the input variables (which depend on managerial choices, and may thus be varied when setting the PL delivery option) and the context data, computes the costs associated to the delivery of one parcel, and provides an evaluation of a potential investment in PL. Details about the input variables and context data, as well as the outputs, are reported in Appendix A.

Appendix B displays instead the set of mathematical formulas of the model. The logic behind the formulas is based on both the interviews with practitioners and literature about last-mile logistics. In the following, there are some references that justify the main choices made (between square brackets there are the formulas they refer to).

- The main operative costs associated to the delivery are the cost of the van – which depends on the travelled distance – and the cost of the driver – which is instead related to the number of worked hours (Mangiaracina et al., 2019) [2, 3, 5];
- These costs are allocated to the number of parcels delivered in the tour (Van Duin et al., 2020) [2, 3, 5, 6];
- The distance travelled in a delivery tour may be found combining two components: the distance from the hub to the delivery area, and the distance within the area to connect the destinations (Figliozzi, 2007) [2, 3, 5];

- Failed deliveries generate additional costs, as they need to be rescheduled in a subsequent tour (Pan et al., 2017) [1, 2];
- PL do not only generate costs associated to the delivery, but also the cost to use the lockers (e.g., energy consumption) (Van Duin et al., 2020) [4];
- The orders not collected by customers from PLs generate an additional cost due to parcels carried back to the hub (Zenezini et al., 2018) [7];
- The NCF and the NPV are reliable measures to evaluate the economic convenience of a solution (Woods and Randall, 1989) [8, 9, 10].

The estimation of the number of parcels delivered per tour is made taking into consideration the most stringent between two constraints, namely the capacity of the van and the number of working hours of the driver. These constraints typically fit different distribution problems. Vehicle capacity is usually valid in the first-mile transport, where a significant quantity of goods is moved, and there may be the risk to exceed the maximum amount that can be carried by the vehicle (Wang et al., 2014). The driver working shift is instead the typical constraint of last-mile deliveries, where flows are much more fragmented, orders are very small and customers to be visited are many and dispersed (Mangiaracina et al., 2019). While the constraint in the HD case is the time of the driver, in the PLs this is not always true: the PL delivery density is higher than that of the HD case (since different parcels are delivered to the same locker), but it is lower if compared to that of the first-mile delivery (where the amount of goods dispatched to one location is much higher). Henceforth, the combination of the two abovementioned constraints was adopted for PLs, and the algorithm can select the most stringent between the two restrictions. In general, when PLs are far from each other (low PL density) the driver spends a great amount of time travelling and, as a result, the working hours are the scarce resource. On the contrary, when PLs are close (high PL density) the capacity of the van becomes the most stringent constraint.

The resulting outputs returned by the model are: PL delivery cost, HD delivery cost, Net Present Value (NPV) of a potential investment in PLs after 3 years and PL payback time.

Model application and results

Base case - Input

In order to answer the RQs, two scenarios are considered: the urban and the rural one. The representative implementation contexts are based on two Italian areas: Milan (urban case) and the countryside of Bergamo (rural case). Despite the different population densities, the delivery destinations may be considered evenly and randomly spread in both cases (Seghezzi et al., 2020). For details about the areas, the reader is referred to Akhavan et al. (2020) for Milan and Lagorio et al., (2014) for Bergamo.

The main input and context data used to run the model, for both the areas, are listed in Table 3.

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The main variables and parameters differentiating the urban and rural cases are the following:

- Delivery tour: the courier, during the 8-hour shift, can deliver up to about 65 orders in urban areas and 44 orders in the rural one, travelling 50 and 200 km respectively within the areas. On the one hand, the higher distances between two consecutives destinations in rural areas increase the driving time and, as a result, reduce the time spent by the driver to perform delivery activities (decreasing the number of served customers). On the other hand, speed limits in rural areas are typically less stringent than within cities.
- PL density: the case of urban deliveries was built assuming a higher density of lockers (average distance between two lockers: 2 km) if compared to the case of rural deliveries (average distance between two lockers: 20 km). This is in line with the different population density of a city if compared to the countryside.
- PL fill rate: the average fill rate coefficient for lockers is 55% in urban areas and 40% in rural ones. Given the 55% fill rate coefficient (i.e., 36 parcels for each cabinet), a vehicle whose full load is 150 average sized parcels can serve up to four cabinets in a shift. The fill rate is higher in urban areas, since online orders are typically concentrated in cities.

- PL annual cost: the annual cost, i.e., land occupation, energy and maintenance costs, is € 5,000 in urban areas and € 3,000 in rural areas. The discrepancy between these two values may be mostly ascribed to the different costs of land occupation.

The presented values underwent three main steps, relying on three different methods.
(i) First, reference values were hypothesised relying on academic literature/secondary sources (i.e., logistics practitioners' journals and reports from both consultancy companies and university research centres). The choice of each variable/parameter was informed by more than one paper/journal (the reference reported in Table 3 is that proposing the value closer to the selected one), and the research team defined a reasonable range that could well suit the considered context, also based on the knowledge gained during former works.
(ii) Second, interviews were performed with different practitioners operating in the field, to discuss the proposed ranges of values, and define the reference ones to be used, based on their experience in the actual areas (real measured cost parameters for the consolidated and well-known HD case, expected values for the novel PL option). Interviews were not used to collect data from scratch since when the number of values to be collected is high, it is easier for interviewees to discuss potential candidates than to hypothesise all of them (Seghezzi and Mangiaracina, 2020).
(iii) Third, some simulations were performed (in collaboration with the same practitioners) to test the reliability of the chosen values for the main variables concerning the delivery tours (please refer to Figure 2). These simulations were made using ArcGIS software – with the embedded VRP-solver component – using real information concerning Milan (for the urban area) and the countryside of Bergamo (for the rural area). Once the demand is simulated in the considered area, and the position of the hubs (which are represented with red triangles) is defined, the software founds the optimal number of vehicles to be used, and the route for each vehicle, minimising the overall travelled distance. Despite some slight differences due to the randomness intrinsic in the simulation process, the main results are aligned to the values chosen. Hence, the values used (and presented in Table 3) may be considered realistic and well representative of the delivery tours of express couriers operating in the two selected areas. Please note that the results of the simulation, as reported in the tables, are computed as the average of the outcomes referred to the different delivery tours.

Figure 2: Results of the simulations for the delivery tours. Source: Esri ArcGIS Pro (Base map: Esri. "Topographic" [basemap]. Scale Not Given. "World Topographic Map". August 3, 2021.

https://services.arcgisonline.com/ArcGIS/rest/services/World_Topo_Map/MapServer. October 5th, 2021).

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Base case - Results

Four elements were considered to evaluate the economic benefits of PLs compared to HD (see Figure 3): the costs for delivering a parcel, the NPV reached after three years for the investment in the PL solution and the associated payback time.

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Considering urban areas, PLs – entailing a delivery cost of about 1.2 €/parcel – allow the courier to save 1.7 €/parcel approximately compared to HD. With such a benefit, an investment in PLs would present a 133k€ NPV after three years that could be repaid in 1.3 years. Considering instead the rural areas, relying on the PLs implies a 1.8 €/parcel delivery cost, and thus a 3.7 €/parcel reduction if compared to HD. In this case, since the saving stemming from the PLs implementation is higher with respect to that measured for urban areas, a potential investment in PLs would be more profitable (NPV is almost the double) and repayable in less than 1 year.

Beyond the specific numerical values, these results allow to draw some general considerations about PLs. First, delivering parcels through PLs imply lower delivery cost with respect to traditional HD also in contexts where e-commerce is still at earlier stages, and this is true for both the urban and the rural cases. Second, the economic benefit stemming from the implementation of PL is so significant that it allows to quickly repay a potential investment in a network of lockers in both urban and rural areas. Third, the savings that PLs entail with respect to HD are greater in rural areas than in urban ones and, aligned to this outcome, the time needed to repay a potential investment for a network of locker is lower in rural areas than in cities. The reason behind this result may be seen as twofold. On the one hand, traditional HD in rural areas is very expensive: the delivery density is very low, since customers live far from each other, and the time needed by the driver to travel the distance between two subsequent destinations is high. Henceforth, the positive effect stemming from the increased delivery density associated to the PL option is boosted. On the other hand, both the operative annual cost (mainly due to the occupation of the land) and the investment for PLs are lower in rural areas than they are in urban ones.

Sensitivity analysis

In order to test the reliability and the robustness of the obtained results, and to make the outcome of the work easier to generalise, some sensitivity analyses were performed on the most significant parameters. More in detail, three different types of analyses were run on four different variables. First, the distance between two PLs (i.e., the density of PLs). Second, the failure rate of traditional HD. Third, the combination of PLs fill rate and their annual working cost. The first two analyses were made for urban areas, while the results of the third (and major) analysis were computed for both the urban and the rural scenarios. The selection of both the parameters and the implementation contexts was made based on interviews with practitioners, who indicated those which were worth additional investigations.

Table 4 summarises the results of the sensitivity analyses on the distance between PLs and the failed delivery rate.

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Distance between PLs. The density of PLs has an impact on the distance travelled by the van when performing the deliveries. In last-mile logistics, the delivery density is a key variable determining the efficiency of the process: the higher the delivery density, the lower the delivery cost per parcel (Boyer et al., 2009). Two scenarios were generated to investigate how the performances of the PL case could worsen – if compared to the base case – when decreasing the density of PLs (i.e., increasing the average distance among them). More in detail, referring to urban environment, beside the base case (2 km), the two considered values are 5 km and 8 km. As shown in Table 4, if increasing the distance between two consecutives PLs from 2 to 8 km, the delivery cost per parcel in the PL option may grow by less than 20%, and the time for repaying the investment becomes slightly lower than 1.5 years. More in detail, the delivery cost linearly increases with the distance among PLs. The reason behind this trend is that the number of PLs visited in the tour does not change; on the contrary, the average distance to be travelled to accomplish the same number of deliveries increases. Despite a greater PL delivery cost, even under "worse" – i.e., lower PL density – conditions, PLs still result to be more efficient with respect to traditional HD, granting reasonable payback time.

Failure delivery rate. In the HD base case, the model considered attended deliveries only: the failure rate of HD was 15% at the first attempt and 20% at the second (and third) attempt. Nevertheless, HD can also be unattended – as an example, when reception boxes are employed. In this case, the parcel is delivered even if the customer is not at home, and the failure rate becomes 0%. A sensitivity analysis on the failure delivery rate is indeed proposed, considering the case of unattended deliveries (i.e., no failed deliveries) and scenarios with intermediate values of failure rates (10% at the first attempt and 15% at the second attempt; 5% at the first attempt and 10% at the second attempt). Even in case of unattended HD (for which the HD delivery cost decreases compared to the base case), the PL option still remains convenient (please refer to Table 4). As a consequence, the saving in the delivery cost entailed by lockers allows to repay the investment in all the considered configurations in a different timespan, but always lower than 2 years. In an unattended HD scenario, the payback time is 1.7 years, compared to 1.3 years of the base case (for urban environments).

Besides the first two sensitivity analyses – each one focussed on one parameter – a third broader analysis was run, aimed at concurrently considering the potential variations of two variables, namely the PL fill rate and the annual working cost (please refer to Figure 4).

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PL annual working cost and fill rate. Indeed, according to both interviews with practitioners and preliminary analyses aimed at varying the values of different parameters, these variables are those impacting the most on both the PL delivery cost and the payback time of a potential investment.

Interviews to both logistics operators and municipalities suggested considering the following values:

- Urban area: annual operating cost ranging from €3,000 to €14,000 per year; average PL fill rate coefficient from 40% to 60%.
- Rural area: annual operating cost ranging from €1,000 to €12,000 per year; average PL fill rate coefficient from 30% to 50%.

Figure 3 displays the results for both urban (top part of the figure) and rural areas (bottom part). The tables on the left exhibit the unitary delivery costs [€/parcel], the tables on the right show the associated payback time [year]. Darker colours are associated to worse economic performances.

In general, the sensitivity analyses show how the outcomes of the base case scenario are robust, and they allow to derive different general considerations. First, independently from the variations in the considered variables, delivering a parcel through PLs is always more efficient than the HD option, in both urban and rural areas. Second, even with a lower fill rate or a higher annual cost, the savings stemming from the implementation of PL solution stay wider in rural areas than in urban ones, due to the much higher HD cost per parcel in an rural area. Considering the single effect of the variations of the two variables, a higher annual cost entails – as expected – an increase in the PL delivery cost (and thus also in the payback time); the same happens if decreasing the PL fill rate. Beside their individual impact, the effect of each factor gets amplified as much as the other one increases, i.e., the same decrease in the PL fill rate has stronger effects if associated to higher annual costs and vice versa (e.g., for urban areas, in case the annual cost is €5,000, decreasing the fill rate from 55% to 45% entails a €0.1 increase in the PL delivery cost; if the annual cost is instead €12,000, the delivery cost increases by €0.3/parcel). These considerations are valid for the both urban and rural areas.

To conclude, the sensitivity analyses confirm that the delivery cost of PL is lower than that of traditional HD, especially if considering rural areas.

Conclusions

This paper reached the defined objective, i.e., developing a model to compare the delivery cost of traditional B2C e-commerce HD and the delivery through PLs, in contexts in which e-commerce is still at early stages, considering both urban and rural areas, overcoming the gaps of existing works. The work shows that:

(RQ1) the average cost for a B2C e-commerce delivery performed through PLs in an urban area is lower if compared to the cost of traditional HD (about 1.2 vs 2.9 €/parcel, thus allowing to save approximately 59%). The sensitivity analyses highlights how the PL delivery cost ranges from a minimum value of 0.9 €/delivery (if the annual cost is 3,000 € and the PL fill rate is 60%) to a maximum value of 2.73 €/delivery (if the annual cost is 14,000 € and the PL fill rate is 40%). The advantages of PLs mainly derive from the increase in the delivery density and the drastic reduction of failed deliveries.

(RQ2) If considering rural areas, relying on PLs implies a 2 €/parcel delivery cost, and thus a 3.4 €/parcel (67%) reduction if compared to HD. In this case, since the saving stemming from the PLs implementation is higher if compared to that measured for urban areas, a potential investment in PLs would be more profitable. On the one hand, traditional home deliveries in rural areas are very expensive; on the other hand, both the operative annual cost and the investment for PLs are lower in rural areas than they urban ones. The sensitivity analyses show that the PL delivery cost ranges from a minimum value of 1.34 €/delivery (if the annual cost is 1,000 € and the PL fill rate is 50%) to a maximum value of 4.45 €/delivery (if the annual cost is 12,000 € and the PL fill rate is 30%).

The present paper has both academic and practical implications.

From the academic perspective, it overcomes all the gaps emerged from the literature review. First, it includes all the type of costs associated to PLs, i.e., transport cost, operating costs, and failed delivery cost, and also the investments, assuming a medium time perspective (evaluating also the payback time and the NPV after three years). Moreover, it clearly compares pure HD and PL delivery options. Second, it develops a model that suits both urban and rural areas, based on all the relevant differential elements. Third, it models a more realistic delivery process: three potential delivery attempts are considered for each delivery; "traditional" home deliveries with no appointments are analysed; the duration of the shift of the driver is included in the cost function.

From the managerial perspective, it provides practitioners with a reliable tool to support the decision-making process about the implementation of HD and PL delivery solutions, to benchmark their costs and identify the main variables and parameters at play. In addition, retailers – if they pay the couriers a fixed amount per outsourced delivery, independently from the selected delivery option – could benefit from the presented results when negotiating the fee paid for PL deliveries. Considering policymakers, the combined analysis of the urban and rural cases offers insights that could be useful in defining planning policies for last-mile deliveries (e.g., adopting measures to promote the use of PL, as it is already happening in Italy with AGCOM).

This model presents some limitations, which suggest directions for future studies. First, even if some sensitivity analyses were performed, the values used to feed the model are considered as deterministic, and thus their variability is only partially envisaged. A subsequent phase of the work could leverage on additional analyses integrating probabilistic distribution of input data. Second, the paper, in line with the stated objective, considers the cost side of the business, and not the revenue one. Despite this entails interesting results, further research efforts could be aimed at evaluating the economic profitability of the solution including the analysis of revenues, to make results even easier to generalise to different merchant-courier agreements (alternative to the fixed-fee one). Despite those limitations and the potential improvements, the authors – as well as the practitioners involved in the study – are confident that the obtained results are coherent with reality and that the stemming conclusions are consistent.

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Appendix A – Variables and parameters

Input variables:

- Hub-PL distance: average distance between the courier's hub and the first PL reached in the delivery tour.
- Density of PL: it is expressed as the average distance between two consecutive PLs (path – and thus not geographical – distances are considered).
- PL capacity: it is intended as the number of compartments in the locker.

Context data:

HD. They describe the main characteristics of the HD case.

- Hub-delivery area distance: average distance between the hub of the courier and the delivery area.
- Average distance within the delivery area: average number of km travelled by the van to perform HDs within the delivery area (i.e., to reach all the customers' locations).
- Deliveries per tour: average number of deliveries per each HD tour.
- HD delivery time: time needed to perform delivery activities at customer's home. It implies waiting for the customer to come, sign and collect the parcel.
- Failed delivery rate: expected rate (expressed as a percentage) of deliveries failed due to the absence of the customer at home; there are two different values referred to the two potential delivery attempts for the same parcel (the probability to fail the first time is different from the probability to fail at the second attempt).

PL. They report all the information about PLs, including physical features, utilisation rate and economic characteristics.

- Average PL fill rate: average percentage of locations actually occupied by parcels.
- PL delivery time: time needed per each parcel after the parcel locker has been reached. It consists in the time needed to open the cabinet and store the parcel.
- PL expired orders: percentage of parcels not collected by the customers within the agreed time windows; those parcels must be collected by the driver and brought back to the hub.
- PL energy consumption: amount of energy (kWh/month) needed by a PL to work.
- PL annual cost: operative cost to run the PL; it includes both land occupation and maintenance costs.

- PL investment: investment needed to purchase and install a PL.

Common. The values common to both the HD and the PL cases mainly refer to the vans.

- Driver cost: cost associated to the driver per time unit.
- Driver working shift: number of consecutive hours in one shift.
- Vehicle cost: cost of the van, which depends on the travelled kilometres.
- Van capacity: maximum load of the vehicle, intended as the maximum number of parcels that can be carried, based on both volume and weight constraints.
- Travel speed: average speed of the van. Values differ in urban and rural areas due to different traffic conditions.

Outputs:

- PL delivery cost, i.e., the average cost to deliver a parcel through the PL option.
- HD delivery cost, i.e., the average cost to deliver a parcel through the HD option.
- Net Present Value (NPV) of a potential investment in PLs, after a period of time of three years (the base case being traditional HD). The computation of the NPV is based on both the initial investment needed to buy and install a PL, and – for each year – the Net Cash Flows (NCF) actualised considering the yearly cost of capital. The NCF is on turns computed based on the annual PL costs (i.e., land occupation, energy and maintenance costs) and the savings entailed by PLs if compared to traditional HD.
- PL payback time, i.e., the time needed to repay a potential investment in the considered network of PLs (the base case still being relying on HD only). The payback time can be computed as the time after which the Net Present Value (NPV) reaches a null value.

Appendix B – Formulas

HD cost (parcels delivered at 1st attempt) [1]

$$\left(1 - FD\ rate_{1st\ attempt}\right) \cdot \left[\frac{Driver\ cost\ \cdot Driver\ working\ shift}{Deliveries\ per\ tour} + \frac{Vehicle\ cost\ \cdot (2 \cdot Average\ distance_{Hub-delivery\ area} + Average\ distance_{delivery\ area})}{Deliveries\ per\ tour}\right]$$

HD cost (parcels not delivered at 1st attempt) [2]

$$\left[FD\ rate_{1st\ attempt}\ \cdot \left(1 - FD\ rate_{2nd\ attempt}\right) \cdot 2 + \left(FD\ rate_{1st\ attempt}\ \cdot FD\ rate_{2nd\ attempt}\right) \cdot 3\right] \cdot \left[\frac{Driver\ cost\ \cdot Driver\ working\ shift}{Deliveries\ per\ tour} + \frac{Vehicle\ cost\ \cdot (2\ \cdot Average\ distance_{Hub-delivery\ area} + Average\ distance_{delivery\ area})}{Deliveries\ per\ tour}\right]$$

PL Delivery cost [3]

$$Driver\ cost \cdot \left[\frac{Average\ distance_{Hub-PL} + (n-1) \cdot Average\ distance_{PL-PL}}{Travel\ speed\ \cdot Deliveries\ per\ tour} + \frac{PL\ delivery\ time}{3600}\right] + \ Vehicle\ cost\ \cdot \left[\frac{2 \cdot Average\ distance_{Hub-PL} + (n-1) \cdot Average\ distance_{PL-PL}}{Deliveries\ per\ tour}\right]$$

PL Expired parcels cost (expired parcels to be moved back to the hub) [4]

$$\%Expired\ parcels \cdot \left\{Driver\ cost \cdot \left[\frac{Average\ distance_{Hub-PL} + (n-1) \cdot Average\ distance_{PL-PL}}{Travel\ speed\ \cdot Deliveries\ per\ tour} + \frac{PL\ delivery\ time}{3600}\right] + \ Vehicle\ cost\ \cdot \left[\frac{Average\ distance_{Hub-PL} + (n-1) \cdot Average\ distance_{PL-PL}}{Deliveries\ per\ tour}\right]\right\}$$

Where:

$FD\ rate_{1st\ attempt}$ = rate of home deliveries that fail at the first delivery attempt [%]

$FD\ rate_{2nd\ attempt}$ = rate of home deliveries that fail at the second delivery attempt [%]

Driver cost = hourly cost of the driver [€/hour]

Driver working shift = duration of the working shift of the driver [hours/shift]

Vehicle cost = fuel and maintenance cost of the vehicle per kilometre [€/km]

Travel speed = average speed of the van [km/h]

Deliveries per tour = number of deliveries scheduled in a delivery tour [deliveries/tour]

n = number of PLs visited in the delivery tour [PL]

PL delivery time = time to deliver a parcel in the PL [s/parcel]

% expired parcels = percentage of parcels not collected by the customers [%]

$Average\ distance_{Hub\text{-}delivery\ area}$ = average distance from the hub to the delivery area [km]

$Average\ distance_{delivery\ area}$ = average distance travelled by the van within the delivery area [km]

$Average\ distance_{Hub\text{-}PL}$ = average distance from the hub to the first PL visited in the PL delivery tour [km]

$Average\ distance_{PL\text{-}PL}$ = average distance between two PLs [km]

$$NPV(T) = -I + \sum_{t=1}^{T} \frac{HD\ cost - PL\ cost}{(1+i)^t}$$

Where:

HD cost = average cost to perform a delivery through the traditional HD mode [€], computed through the model as per formulas above

PL cost = average cost to perform a delivery through the traditional HD model [€], computed through the model as per formulas above

I = initial investment to install the PL

i = cost of capital

T = time horizon to evaluate the convenience to invest in Parcel Locker

Paper	Objective	Delivery method	Transportation cost	Opening cost (investment)	Operating cost	Failed delivery cost
Iwan et al., (2016)	Case study to calculate costs	PL vs. HD	x			
Deutsch and Golany (2018)	PL location problem to maximise profit	PL		x	x	
Veenstra et al. (2018)	VRP and location problem to minimise costs	PL and HD	x	x		
Song et al., (2019)	Simulation to calculate costs	PL vs. HD vs. HD + CDP	x			x
Sitek and Wikarek (2019)	VRP to minimise costs	PL, considering capacity and alternative delivery points	x			x
Sitek et al. (2020)	VRP to minimise costs	PL, considering capacity, alternative delivery points and delivery windows	x			x
Van Duin et al. (2020)	Simulation to calculate costs	HD + PL vs. HD + CDP vs. HD + PL + CDP	x			x
Yang et al. (2020)	Location problem to minimise costs	PL	x	x	x	
Redi et al. (2020)	VRP to minimise costs + computational experiment to calculate costs	PL vs. HD	x		x	
Lin et al. (2020)	VRP to minimise costs (units) + experiment	PL vs. HD with cargo bikes		x		
Enthoven et al. (2020)	VRP and location problem to minimise costs	Mobile PL	x			
Wang et al. (2020 a)	VRP and location problem to minimise costs	Mobile PL with aggregation problem vs. PL without the aggregation problem		x	x	
Faugère and Montreuil (2020)	Fixed and modular configuration Locker Bank Design Problem to maximise profit	Fixed PL vs. Mobile PL		x	x	
Wang et al. (2020 b)	Location problem to minimise costs	Mobile PL	x		x	
Schwedfeger and Boysen (2020)	Dynamic location problem to minimise costs	Mobile PL		x		

Table 1: Previous literature and considered costs

Paper	Objective	Comparison	Transportation cost	Opening cost (investments)	Operating cost	Failed delivery cost	Investment evaluation	Area	Considered variations			Delivery process modelling			Best	Unit of analysis	Results (savings)
									Speed	Delivery density	Land occupation	Additional attempts	Traditional delivery	Drivers shift cost			
Iwan et al., (2016)	Case study to calculate costs	PL vs. HD	x				No	Urban	x			0	x		PL	Fuel costs per year	95%
Song et al., (2019)	Simulation to calculate costs	PL vs. HD vs. HD+CDP	x			x	No	Urban				2	x		PL	Delivery cost per 200 deliveries	Up to 71.3%
Van Duin et al. (2020)	Simulation to calculate costs	HD+PL vs. HD+CDP vs. HD+PL+CDP	x			x	No	Urban		x		1			HD (34%) + PL (66%)	Delivery cost per day	16%
Redi et al. (2020)	VRP problem to minimise costs + computational experiment to calculate costs	PL vs. HD	x		x		No	Urban				0	x		PL	Delivery cost per day	70.4%
Present paper	Analytical model to calculate costs	PL vs. HD	x	x	x	x	Yes (NPV, Payback Time)	Urban and rural	x	x	x	2	x	x	PL	Total cost per delivery	T.B.D.

Table 2: Selection of relevant papers, and comparison with the present research

HD		Main sources		
		Literature	Interviews	Secondary sources
Average distance within the delivery area, urban area [km]	50	Edwards et al. (2010)	Express courier	
Average distance within the delivery area, rural area [km]	200	Cuzzocrea et al. (2019)	Express courier	
Hub-delivery area distance, urban area [km]	15	Figliozzi et al. (2007)	Express courier	
Hub-delivery area distance, rural area [km]	35	Figliozzi (2010)	Express courier	
Deliveries per tour, urban area [parcels/tour]	65	Giuffrida et al. (2019)	Express courier	
Deliveries per tour, rural area [parcels/tour]	44	Mangiaracina et al. (2016)	Express courier	
HD delivery time [min/parcel]	4	Siikavirta et al. (2002)	Express courier	
Failed delivery rate, first attempt [%]	15	Allen et al. (2018)	Express courier	
Failed delivery rate, second attempt [%]	20	Song et al. (2009)	Express courier	
PL				
Hub-PL distance, urban area [km]	20		Retailer, Express courier	Research centre report
Hub-PL distance, rural area [km]	50		Retailer, Express courier	Research centre report
Average distance between two PLs, urban areas [km]	2		PL producer	Consultancy case study report
Average distance between two PLs, rural areas [km]	20		Retailer, Express courier	Consultancy case study report
Number of locations in a PL	65		PL producer	Website of PL producers
Average PL fill rate, urban areas [%]	55		Retailer, Express courier	Logistics practitioners' journal
Average PL fill rate, rural areas [%]	40		Retailer, Express courier	Logistics practitioners' journal
PL delivery time [s/parcel]	20		PL producer	Website of PL producers
PL expired orders [%]	1		Retailer, Express courier	Logistics practitioners' journal
PL energy consumption [kW/month]	90	Pålsson et al. (2017)		Website of PL producers
PL annual cost, urban area [€/year]	5,000		Milan municipality operator	Logistics practitioners' journal
PL annual cost, rural area [€/year]	3,000		Milan municipality operator	Logistics practitioners' journal
PL investment [€]	20,000		Retailer	Website of PL producers
Common				
Driver cost [€/h]	16.7	Seghezzi et al. (2020)	Express courier	
Driver working shift [h]	8	Goel and Rousseau (2012)	Express courier	
Vehicle cost [€/Km]	0.36	Giordano et al. (2018)		A.C.I. (Automobile Club of Italy) website
Van capacity [parcels]	150	Böröcz, and Singh (2018)		Website of van producers
Travel speed, urban area [km/h]	15	Allen et al. (2018)	Express courier	
Travel speed, rural area [km/h]	30	Giuffrida et al. (2019)	Express courier	

Table 3: Input and context data for the base case

	Urban area				Rural area			
	Base case (15%-20% failed delivery)	**10%-15% failed delivery**	**5%-10% failed delivery**	**No failed deliveries (unattended HD)**	**Base case (15%-20% failed delivery)**	**10%-15% failed delivery**	**5%-10% failed delivery**	**No failed deliveries (unattended HD)**
PL delivery cost [€/parcel]	(Base case, PL density: 2 km) 1.2				1.8			
	(PL density: 5 km) 1.3							
	(PL density: 8 km) 1.4							
HD delivery cost [€/parcel]	2.9	2.8	2.6	2.5	5.5	5.2	4.9	4.7
PL NPV (3 years) [€]	132,921	111,499	91,725	73,598	315,730	280,031	247,077	216,870
PL Payback Time [year]	1.3	1.4	1.5	1.7	0.8	0.9	1	1

Table 4: Sensitivity analysis on PL density and Failed delivery rate

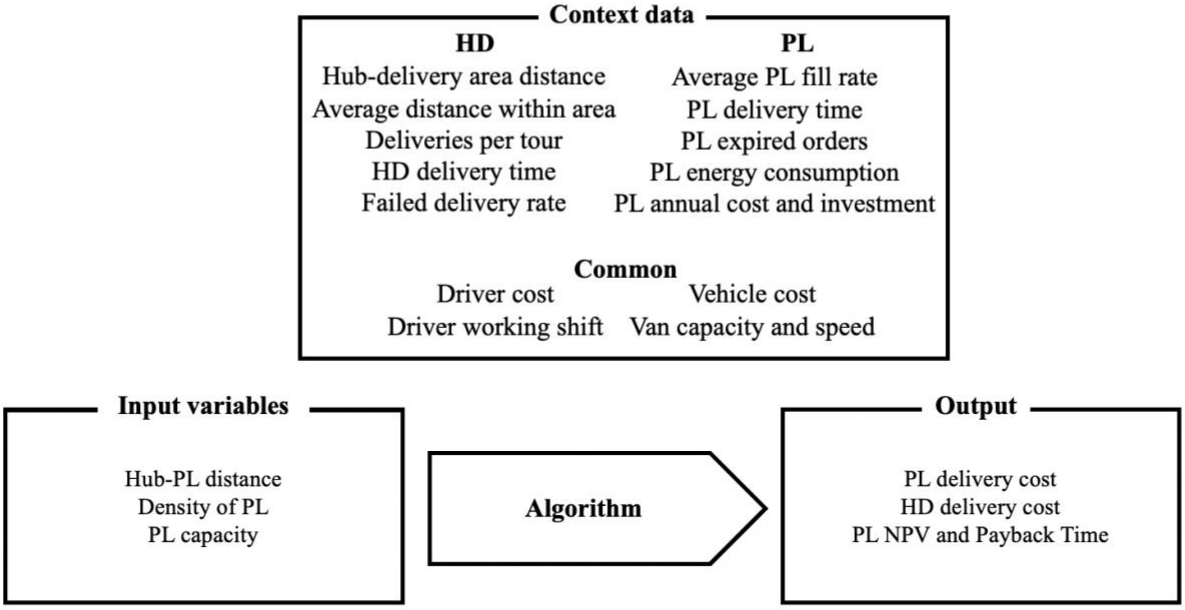
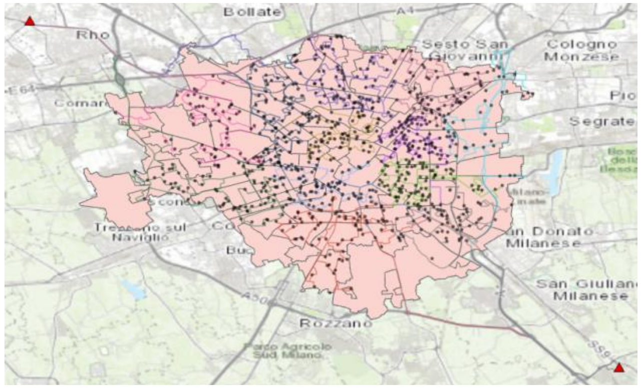
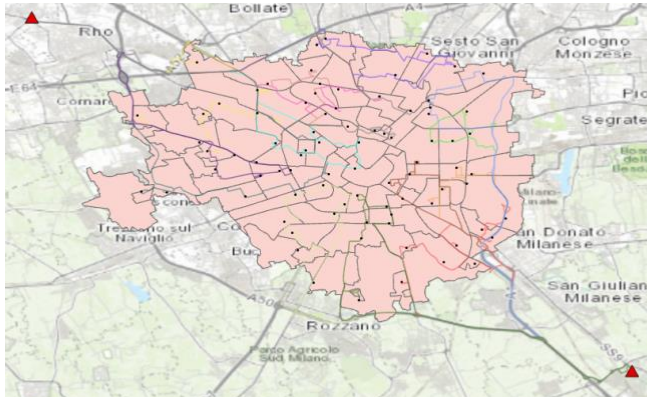


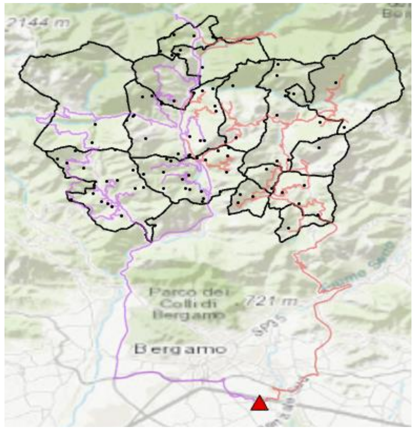
Figure 1: Model architecture



Urban area, HD	Input Data	Simulation results
Deliveries per tour	65	66.7
Hub-delivery area [km]	15	15.9
Average distance within the delivery area [km]	50	47
Total travelled distance [km]	*80*	*78.8*



Urban area, PL	Input Data	Simulation results
Hub-PL distance [km]	20	17
Average distance between two PLs [km]	2	2.4
Total travelled distance [km]	*48*	*46*



Rural area, HD	Input Data	Simulation results
Deliveries per tour	44	46.5
Hub-delivery area [km]	35	38.5
Average distance within the delivery area [km]	200	188
Total travelled distance [km]	*270*	*265*

Rural area, PL	Input Data	Simulation results
Hub-PL distance [km]	50	53
Average distance between two PLs [km]	20	19
Total travelled distance [km]	*200*	*182*

Figure 2: Results of the simulations for the delivery tours. Source: Esri ArcGIS Pro (Base map: Esri. "Topographic" [basemap]. Scale Not Given. "World Topographic Map". August 3, 2021. https://services.arcgisonline.com/ArcGIS/rest/services/World_Topo_Map/MapServer. October 5th, 2021).

	Urban area	Rural area
PL delivery cost [€/parcel]	1.2	1.8
HD delivery cost [€/parcel]	2.9	5.5
PL NPV (3 years) [€]	132,921	315,730
PL Payback Time [year]	1.3	0.8

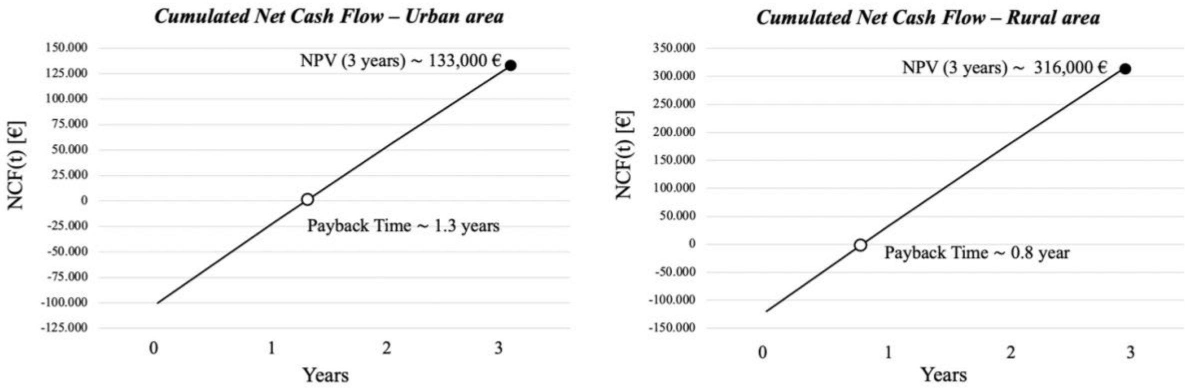


Figure 3: Results of the model application – Base case

Urban area – PL delivery cost

PL fill rate	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,000	14,000
	Annual cost [€/year]											
60%	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
59%	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
58%	0.9	1.0	1.1	1.2	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1
57%	0.9	1.0	1.1	1.2	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1
56%	0.9	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1
55%	1.0	1.1	**1.2**	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.1	2.2
54%	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.1	2.2
53%	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.8	1.9	2.0	2.1	2.2
52%	1.0	1.1	1.2	1.3	1.4	1.6	1.7	1.8	1.9	2.0	2.1	2.3
51%	1.0	1.1	1.2	1.3	1.4	1.6	1.7	1.8	1.9	2.0	2.1	2.3
50%	1.0	1.1	1.2	1.4	1.5	1.6	1.7	1.8	2.0	2.1	2.2	2.3
49%	1.0	1.1	1.3	1.4	1.5	1.6	1.7	1.9	2.0	2.1	2.2	2.4
48%	1.0	1.1	1.3	1.4	1.5	1.6	1.7	1.9	2.0	2.1	2.2	2.4
47%	1.0	1.1	1.3	1.4	1.5	1.7	1.8	1.9	2.0	2.2	2.3	2.4
46%	1.1	1.2	1.3	1.5	1.6	1.7	1.8	2.0	2.1	2.2	2.4	2.5
45%	1.1	1.2	1.3	1.5	1.6	1.7	1.8	2.0	2.1	2.2	2.4	2.5
44%	1.1	1.2	1.3	1.5	1.6	1.8	1.9	2.0	2.2	2.3	2.4	2.6
43%	1.1	1.2	1.4	1.5	1.7	1.8	1.9	2.1	2.2	2.4	2.5	2.7
42%	1.1	1.2	1.4	1.5	1.7	1.8	1.9	2.1	2.2	2.4	2.5	2.7
41%	1.1	1.3	1.4	1.5	1.7	1.8	2.0	2.1	2.3	2.4	2.6	2.7
40%	1.1	1.3	1.4	1.5	1.7	1.8	2.0	2.1	2.3	2.4	2.6	2.7

Urban area – Payback Time

PL fill rate	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,000	14,000
	Annual cost [€/year]											
60%	1.0	1.0	1.1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.9	2.1
59%	1.0	1.0	1.1	1.2	1.3	1.3	1.4	1.6	1.6	1.8	2.0	2.3
58%	1.0	1.1	1.2	1.2	1.3	1.4	1.5	1.7	1.7	1.8	2.2	2.5
57%	1.0	1.1	1.2	1.2	1.3	1.4	1.5	1.7	1.7	1.8	2.2	2.5
56%	1.1	1.1	1.2	1.3	1.4	1.5	1.6	1.8	1.7	1.8	2.4	2.7
55%	1.1	1.2	**1.3**	1.3	1.4	1.6	1.7	1.9	1.8	1.9	2.6	2.9
54%	1.1	1.2	1.3	1.3	1.4	1.6	1.7	1.9	1.8	1.9	2.6	2.9
53%	1.2	1.2	1.3	1.4	1.5	1.6	1.8	2.0	1.9	2.0	2.8	3.2
52%	1.2	1.3	1.4	1.5	1.6	1.7	1.9	2.1	1.9	2.2	3.0	3.6
51%	1.2	1.3	1.4	1.5	1.6	1.7	1.9	2.1	1.9	2.2	3.0	3.6
50%	1.2	1.3	1.4	1.5	1.7	1.8	2.0	2.2	2.0	2.3	3.3	4.0
49%	1.3	1.4	1.5	1.6	1.8	1.9	2.1	2.4	2.2	2.5	3.7	4.5
48%	1.3	1.4	1.5	1.6	1.8	1.9	2.1	2.4	2.2	2.5	3.7	4.5
47%	1.3	1.4	1.6	1.7	1.9	2.1	2.3	2.6	2.3	2.7	4.2	5.3
46%	1.4	1.5	1.7	1.8	2.0	2.2	2.5	2.9	2.4	2.8	5.0	6.5
45%	1.4	1.5	1.7	1.8	2.0	2.2	2.5	2.9	2.4	2.8	5.0	6.5
44%	1.5	1.6	1.8	1.9	2.1	2.4	2.7	3.1	2.6	3.1	5.8	8.1
43%	1.6	1.7	1.9	2.0	2.3	2.6	3.0	3.5	2.8	3.5	7.0	10.6
42%	1.6	1.7	1.9	2.0	2.3	2.6	3.0	3.5	2.8	3.5	7.0	10.6
41%	1.6	1.8	2.0	2.2	2.4	2.8	3.2	3.8	3.1	4.1	8.8	15.3
40%	1.6	1.8	2.0	2.2	2.4	2.8	3.2	3.8	3.1	4.1	8.8	15.3

Rural area – PL delivery cost

PL fill rate	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000
	Annual cost [€/year]											
50%	1.3	1.5	1.6	1.7	1.8	1.9	2.1	2.2	2.3	2.4	2.5	2.7
49%	1.3	1.5	1.6	1.7	1.8	2.0	2.1	2.2	2.3	2.5	2.6	2.7
48%	1.3	1.5	1.6	1.7	1.8	2.0	2.1	2.2	2.3	2.5	2.6	2.7
47%	1.4	1.5	1.6	1.7	1.9	2.0	2.1	2.3	2.4	2.5	2.6	2.8
46%	1.5	1.6	1.7	1.9	2.0	2.1	2.3	2.4	2.5	2.7	2.8	2.9
45%	1.5	1.6	1.7	1.9	2.0	2.1	2.3	2.4	2.5	2.7	2.8	2.9
44%	1.5	1.6	1.8	1.9	2.0	2.2	2.3	2.4	2.6	2.7	2.9	3.0
43%	1.5	1.6	1.8	1.9	2.1	2.2	2.3	2.5	2.6	2.8	2.9	3.1
42%	1.5	1.6	1.8	1.9	2.1	2.2	2.3	2.5	2.6	2.8	2.9	3.1
41%	1.5	1.6	1.8	1.9	2.1	2.2	2.4	2.5	2.7	2.8	3.0	3.1
40%	1.5	1.6	**1.8**	1.9	2.1	2.2	2.4	2.5	2.7	2.8	3.0	3.1
39%	1.5	1.7	1.8	2.0	2.1	2.3	2.4	2.6	2.7	2.9	3.0	3.2
38%	1.8	2.0	2.1	2.3	2.4	2.6	2.7	2.9	3.0	3.2	3.4	3.5
37%	1.9	2.0	2.2	2.3	2.5	2.7	2.8	3.0	3.1	3.3	3.5	3.6
36%	1.9	2.1	2.2	2.4	2.6	2.7	2.9	3.1	3.2	3.4	3.5	3.7
35%	2.0	2.1	2.3	2.5	2.6	2.8	3.0	3.1	3.3	3.5	3.6	3.8
34%	2.0	2.2	2.4	2.5	2.7	2.9	3.1	3.2	3.4	3.6	3.8	3.9
33%	2.1	2.3	2.4	2.6	2.8	3.0	3.2	3.3	3.5	3.7	3.9	4.0
32%	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.4	3.6	3.8	4.0	4.2
31%	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.5	3.7	3.9	4.1	4.3
30%	2.3	2.5	2.7	2.9	3.1	3.3	3.5	3.7	3.9	4.1	4.3	4.5

Rural area – Payback Time

PL fill rate	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000
	Annual cost [€/year]											
50%	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.8
49%	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.9
48%	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.9
47%	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.9	0.9	0.9
46%	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.9	0.9	0.9	1.0	1.0
45%	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.9	0.9	0.9	1.0	1.0
44%	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.0	1.1
43%	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.0	1.1	1.2
42%	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.0	1.1	1.2
41%	0.7	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.1	1.1	1.2	1.3
40%	0.7	0.8	**0.8**	0.8	0.9	0.9	0.9	1.0	1.1	1.1	1.2	1.3
39%	0.8	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.3	1.4
38%	1.0	1.1	1.1	1.2	1.3	1.4	1.5	1.6	1.8	2.0	2.2	2.4
37%	1.1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.9	2.1	2.4	2.7
36%	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.9	2.1	2.3	2.6	3.0
35%	1.2	1.3	1.3	1.4	1.6	1.7	1.8	2.0	2.3	2.5	2.9	3.4
34%	1.2	1.3	1.4	1.5	1.7	1.8	2.0	2.2	2.5	2.8	3.3	3.9
33%	1.3	1.4	1.5	1.6	1.8	1.9	2.2	2.4	2.8	3.2	3.8	4.6
32%	1.4	1.5	1.6	1.7	1.9	2.1	2.4	2.7	3.1	3.6	4.4	5.7
31%	1.5	1.6	1.7	1.9	2.1	2.3	2.6	3.0	3.5	4.3	5.4	7.3
30%	1.6	1.7	1.8	2.0	2.3	2.5	2.9	3.4	4.1	5.1	6.8	10.1

Figure 4: Results of the sensitivity analysis – Annual cost and Fill Rate