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Multi-Criteria Simulation-Optimization Analysis of Usage of Automated Parcel Lockers: A Practical Approach

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Abstract: The rapid growth of electronic commerce is having an impact on the way urban logistics are organized. In metropolitan settings, the last-mile delivery problem, i.e., the problem regarding the final stage of delivering a shipment to a consumer, is a major concern due to its inefficiency. The development of a convenient automated parcel lockers (APLs) network improves last-mile distribution by reducing the number of vehicles, the distances driven, and the number of delivery stops. Using automated parcel lockers, the last-mile issue could be overcome for the environment's benefit. This study aimed to define and validate an APL network containing hundreds of APLs with the use of an example made up of real case study data from the city of Poznań in Poland. The goal of this research was to use mathematical programming for optimization and simulation to tackle the facility location problem for automated parcel lockers through a practical approach. Multi-criteria simulation-optimization analysis was used to assess the data. In fact, the simulation was carried out using Anylogic software and the optimization with the use of the Java programming language and CPLEX solver. Three years were simulated, allowing for comparable results for each year in terms of expenses, e-shoppers, APL users, and demand evolution, as well as achieving the city's optimal locker usage. Finally, encouraging conclusions were obtained, such as the relationship between the demand and the number of lockers, along with the model's limitations.

Keywords: automated parcel locker; last-mile delivery problem; facility location problem; simulation; multi-criteria optimization; exact approach; mathematical programming

MSC: 68R05; 90B06; 90B50; 90C29; 90C90

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1. Introduction

As the popularity of online shopping has grown, so has the need for individual deliveries, resulting in an increase in the number of cargo vehicles moving through cities. As a result, the obstacles in product distribution have intensified [1–3], directly affecting the logistics systems in urban areas, where traffic congestion and accessibility are important factors [3]. Despite the fact that these cars contribute significantly to traffic congestion and CO_2 emissions, they are crucial to urban economies because they bring items to commercial enterprises that meet the population's consumption demands [4–6]. Several studies have established policies and models in this context based on the city logistics approach to decrease the unintended consequences of urban freight, such as congestion, loss of parking spots, lack of mobility, contamination of the environment and noise, and accidents [7]. Attended house deliveries (AHD) are frequently chosen by consumers in the business-to-consumer (B2C) industry over e-commerce. In terms of service and programming expenses, this method of delivery is the most troublesome [4]. The carriers in this mode make multiple stops along the way and rely on the presence of a human in the specified location to finish the delivery [8]. In their study, Song et al. [9] discovered that 25% of deliveries are not completed on the first try.

It is in this context that automated parcel lockers first emerged. Since the package is delivered directly to the locker, then it is the customer who must go to pick it up. With this facility implementation, it is possible to avoid re-deliveries due to the absence of the client at home or the fault of the driver due to not being able to find the address. Furthermore, the deliveries and the transport company's trips are optimized since many packages are delivered at a single point of collection, the Automated Parcel Locker (APL). Thus, this study aims to assess APL as a last-mile solution, considering a mathematical model that allows the optimization of usage of automated parcel lockers located in Poznan, Poland, where the simulation has been carried out. That is, solving the facility location problem in order to maximize the profits and minimizing the costs [10–12].

Hence, the research flow consists of the following steps. We firstly review the relevant literature in order to identify potential synergies with existing literature. Thus, Section 2 provides a literature review with the main references on the subject. That includes problem contextualization, methodologies, and conclusions that may enhance the position of our work paper. Simulation and optimization model definition, design, and implementation is the following step conjointly with data collection as can be shown in Section 3. Finally, Sections 4–6 provide an analysis of the main findings, as well as discussion and conclusions.

2. Literature Review

This section presents a description of the work related to APLs which helps the reader to understand our model. The use of APLs is an important step forward in the development of the last mile distribution in urban delivery of goods and merchandises. Nowadays, the use of APLs has been revealed as a very convenient experience for many customers [13,14], apart from its suitability for parcel urban logistics [15]. Its success is mainly due to the failed delivery problems observed in the urban distribution of goods [16]. Furthermore, some authors [17] has recently pointed out the increasing popularity of APLs among customers, when they have to choose the delivery mode and pick-up system for their purchases. Therefore, an optimum design of the urban network of APLs is needed considering their potential population of users, their associated costs and their efficiency. Thus, developed an initial paper [18] to optimize the APLs network, which has been complemented by the study [19], in which authors designed some accurate models to build an APLs distribution structure. Another important aspect of the APLs appropriateness for last mile urban distribution is their contribution to the improvement of pollution in urban centers [20,21], due to the fact of the substitution effect in relation to delivery vans. Likewise, the COVID-19 outbreak and its evolution during the years 2020–2021 has accelerated the use of e-commerce and, as a consequence, the number of APLs in the urban areas have mushroomed [22]. Thus, this boom of e-commerce has involved the need for optimizing the APLs network using different methodologies of simulation-optimization techniques. For instance, research [23] designed some interesting optimization models to implement the APLs network structure in Singapore. Similarly [6], built an agent-based simulation model to evaluate the current APLs network in the Brazilian city of Belo Horizonte. The utilization of parcel lockers in a crowdshipping network in case of Melbourne [24] allows for shorter trip detour and better geographical coverage. Authors [24] develop a model for locating parcel lockers and allocating delivery task. In research paper [25], authors consider the use of lockers in parcel delivery. Study of routing problems wherein one or more vehicles are deployed to deliver packages directly to clients or lockers [25]. Authors [25] examine the implications of incorporating lockers when these problems include time constraints. Authors propose new formulations for these problems, as well as some valid inequalities and a branch-and-cut algorithm. Furthermore, researchers investigate the distinction between routing problems with lockers and classical routing challenges. Another research paper [26] scrutinize the impact of parcel lockers on travel distances as well as Carbon dioxide emission. Authors demonstrate that, in certain circumstances, parcel lockers positively contribute to both of the previous mentioned performance indices. In paper [27] authors present an approach for designing joint delivery networks in urban areas enhanced by employing parcel lockers. This model is divided into two levels, with the lower level dealing with multi-depot capacitated vehicle routing problems (MDCVRP) for a bundle of depots and lockers, while the upper level is a (minimum-cost) parcel network flow problem (PNFP) considering goods supplied among distribution centers and storage areas, as well as the placement and size of storage. A hybrid algorithm integrating a Genetic Algorithm with the Lin-Kernighan Heuristic has been developed. The GA focuses on finding solutions for the PNFP. Once the package flow paths have been resolved, the LKH optimizes vehicle flow. Different study [28] proposes six mathematical models to different crowdsourced delivery operation modes are quantified. Numerous realistic aspects, such as the most recent service time for each task, task cancellation rate, and task range distribution, are also considered. Authors investigate [29] a last-mile delivery approach in the augmented system with three service modes: home delivery plus pickup, parcel locker delivery plus pickup, and home or parcel locker delivery plus pickup. Problem considered [29] outlines further locker pickup and delivery options. The topic is known as the vehicle routing problem with simultaneous pickup and delivery and parcel lockers (VRPSPDPL). The goal is to minimize the total traveling cost [29]. Paper [30] examined consumers' preferences for receiving parcels that are ordered online, and the findings indicate that changes in prices have a considerable significantly affect on utility. Author [31] investigate the relative performance of the two frequently used material convergence in humanitarian logistics, which corresponds to the movement of relief supplies from donor sites to distribution centers in disaster areas, from which the final deliveries are done to survivors. Considered approaches [31] in terms of their ability to facilitate effective last-mile delivery. An extended version of the Vehicle Routing Problem with Shipment Consolidation (VRPC) is examined by the authors [32]. Model considers not only split deliveries, but also shipment transfers between different vehicles at certain customer locations (a process referred to as mid-route shipment consolidation) [32]. Researchers [33] create a toolkit for investigating the long-term viability of last-mile logistics and distribution methodologies, employing (1) a centralized distribution network with a click and collect option, (2) a decentralized distribution network with a home-delivery option, and (3) a distributed network due to a crowd logistics concept. A system dynamics [33] for a case study of a local food cooperative and a logistics service provider in Austria, simulation and a multi-objective decision support were employed to evaluate the sustainability performance of distribution channel options. Results [33] demonstrate that the most practical and long-lasting solution is to combine the two players into a distributed network strategy built on the idea of crowd logistics.

2.1. Last-Mile Delivery Problem (L-MDP)

(1) In logistics world, the process's last step, which is bringing the merchandise to the way out the door of the shopper—is many times the most un-proficient, costly and contaminating piece of this interaction, involving up to 28% of the complete expense of delivery [34,35]. E-commerce-related traffic growth worsens the already precarious state of cities. primarily due to the air pollution (CO2, NOx), increasing noise, and increased risk of accidents [36,37]. Tracking down ways of further developing this last stage is known as the Logistics Last Mile Problem.

(2) Until now, online product deliveries were made straightforwardly to the consumer's door with the problems that this entails and that make the Last Mile so expensive and inefficient:

(3) The absence of significant estimation: business-to-shopper deliveries frequently include one parcel per stop, compared with many parcels per delivery up to that point [38].

(4) The difficulty in locating the particular home address of the end client, either in large condominiums in the city, or in country region, where the roads may not have proper signs, and the clients may live in a remote farmhouse or a little local area [38].
(5) The 'Not-at-Home Issue', particularly when the end shopper requires the recipient to sign a receipt confirming delivery, resulting in a high delivery failure rate and empty trip rates [38].

2.2. Studies on the Optimization of Automated Parcel Lockers (APLs)

With the burst onto the scene of automated parcel lockers in the logistics business a new paradigm has emerged. So far, customers were accommodated as they were used to receive the deliveries at home. However, it is no longer like that, parcel lockers pose the alternative to clients to go to a point to collect their bundles. For this reason, the APL optimal location problem acts as the key factor in consumer willingness to use this service. Although the subject of APLs is relatively new, this study is not the first one that tries to give an answer to this problem. There exists research [39] that propose solution based on the crowd. This consists of collecting and delivering parcels using individuals (neighbours). The approach utilizes circle packing to compute the number of neighbours needed, the number of parcels they must manage and the corresponding reward. A research study was carried out on the 12th district of Paris (France) dataset. This study makes three important contributions. To begin, they investigated the ability of crowd logistics to reduce delivery malfunction and improve service level in urban deliveries, with an emphasis on environmental and economic concerns. Second, they present a novel method for calculating the number of neighbours and parcels to deliver using a new way to modelling parcel delivery by individuals in metropolitan environments. Finally, they provide a new simulation environment after adjusting the model's parameters. Their findings indicate the potential of building a network of neighbours to avoid delivery failure using data on parcel delivery in Paris's 12th district and population density. In paper [40] authors present development of research addressing this topic. In this study, an agent-based simulation model (ABSM) is used to evaluate the deployment of DL and the exclusion of the third delivery attempt in the city of Belo Horizonte, Brazil. By adjusting delivery locker implementation and excluding the third attempt, four scenarios were created, allowing for comparable results in terms of gains and operational and external expenses for each agent (emission, noise, and congestion). The scenario that was most similar to the existing reality produced the most negative outcomes. The introduction of the lockers improves this scenario by minimising re-delivery and truck distance travelled. The advantages are significantly greater when the potential of three delivery attempts is eliminated. Lockers also facilitate carriers to reduce the number of trucks required for delivery, enabling them to increase earnings. In summarised study [41] author presents findings of a demand assessment for an automated parcel locker (APL) system that is currently in use. The potential demand for APL was assessed using a two-stage approach. Based on Random Utility Modelling, they disclose the current demand for both attended and unattended deliveries in the first step. Then they calculate the time spent on grocery shopping and see how much time could be saved if the shopping and pickup tasks were combined. They found out what consumers' current tastes and behaviours are when it comes to using post office channels (for instance: from 71% for perfumes and cosmetics to 88% for clothing). The discrete choice modelling results revealed that when online customers choose a delivery channel, both economic and spatial factors are important. The suggested APL system's location, i.e., 24/7 minimarkets, would minimize walking time for the pick-up procedure by 20% to 47%, depending on post office locations in relation to online shoppers' dwellings. Many new challenges emerged as a consequence of the SARS-CoV-2 pandemic, for example, governments have sanctioned restrictions such as lockdowns, causing supply chain shocks at multiple levels [42]. Additionally, due to the temporary spike in mail order demand during the lockdowns, delivery services reached their capacity limits [42]. Utilizing (outdoor) parcel lockers where customers can pick up their orders whenever they want while maintaining physical distance is one way to support supply chain viability at the last-mile delivery tier [42]. It is well known that the location selection of such lockers is crucial to their success. Another crucial issue is the need to accommodate the (uncertain) customer demand for various commodities in the compartment structure of the parcel lockers [42]. One optimization problem is created by combining the planning problems [42]. Given a budget in which to invest, the goal is to maximize a linear function (e.g., expected profits) of the covered demand. A formulation for integer linear programming is proposed, and a reformulation based on Benders decomposition is derived. Benders cuts can be separated in linear time. A performance analysis of computational experiments shows that the developed algorithms are capable of solving large-scale problem instances. A sensitivity analysis demonstrates the effect of different problem parameters on the obtained solutions [42]. The authors also present a case study based on real-world data from Austria. The findings indicate that using parcel lockers can help sustain supply chain viability at the last-mile distribution tier. Furthermore, the low investment cost yields promising returns. The findings also suggest that small and medium-sized compartments should be preferred over large and x-large compartments in dispatch locker compartment design [42]. In recently published research [43] authors explained an approach to the last mile delivery problem in which parcel lockers, in addition to serving as order collection points for customers, are also used as transshipment nodes in a 2-echelon delivery system. Taken into account, that a customer (irregular courier) visiting a locker may accept reimbursement to make a delivery to another client on their regular travel path [43]. Research recommend that customers who prefer to self-pick up their orders, as well as customers who prefer home delivery, share locker facilities to make better use of the existing available storage space [43].

2.3. Facility Location Problem (FLP)

Facility location problems are concerned with deciding where to locate a facility (often from a list of integer possibilities) in order to best meet the required constraints. Choosing a factory location that minimizes total weighted distances from suppliers and customers, where weights represent the difficulty of transporting materials, is frequently an issue. The solution to this problem provides the highest profit option that best serves the needs of all e-shoppers [41].

The problem is often defined as a set of customers D, a set of facilities F, a fixed cost for opening each facility, and a variable cost for each facility. The aim is to search for the subset S of facilities that should be opened and an assignment of S to D such that all customers will be serviced by a facility and such that the sum of fixed costs, variable costs, and transportation costs (modeled using distance) is minimized [44].

These issues have been extensively investigated in the literature and are frequently solved with an approximation algorithm. The approximation algorithm seeks a feasible (near optimal) solution in which:

A: The algorithm will terminate computations after a predetermined number of steps (for instance: number of customers and facilities)

B: There is an estimation ratio such that the obtained solution is within a certain margin of the optimal solution [45].

3. Methodology

This case study focused on Poland, which is a country that has companies that are well-positioned in the APL market with a dense locker distribution. Specifically, the study centered on the Polish city of Poznan. All the information and data needed to solve the facility location problem, that is, opening and decommissioning costs, service and maintenance costs, population, e-shoppers, APL users, and demand forecasts, came from company A.

The procedure is the following, first an APL mathematical model is presented, and then the model is embedded in the simulation-optimization structure. This late solved using CPLEX API designed by IBM® for Java. Next, a 3-year simulation is run and finally a set of results are obtained. The decision of using the CPLEX API for Java environment is motivated by the simulation framework, that is built in the Java-based language Anylogic software.

3.1. Multi-Criteria Cost-Oriented Automated Parcel Lockers Optimization Model (MC-CoAPL)

The non-dominated solution set of multi-criteria mathematical programming model [46] can be partially obtained by the parametrization on λ of the weighted-sum program [47]:

Model M_λ

Maximization or minimization of $\sum_{k=1}^{m} \lambda_k f_k$

subject to some specific model constraints (as it is formulated in model presented in this paper (Equations (1)–(10)), where $\lambda_1 > \lambda_2 > \mathrm{I} > \lambda_m$; $\lambda_1 + \lambda_2 + \mathrm{I} + \lambda_m = 1$.

Where f_k is defined as criterion f in a multi-criteria objective function for a number of criteria from $k = 1$ to $k = m$.

It is well known, however, that the non-dominated solution set of a multi-criteria mathematical program such as not be fully ascertained even if the entire parametrization on λ is attempted (e.g., [48]). To find unsupported non-dominated solutions, some upper bounds on the objective functions should be added to (e.g., [49]). Important different approach for multi-objective algorithm [50] is a genetic algorithm platform with a high adaptability, which enable application to a wide range of subjects. The objective of any distribution and delivery company is the speed and effectiveness of parcel delivery, always seeking to improve and optimise its services [37], considering also the environmental impact of this process [51,52].

This APL optimization model is defined over the same set of nodes i ∈ I and j ∈ J representing, respectively, the customers and districts. Thus, the optimization model searches for the optimal assignment of customers to districts and the APL optimal location with the objective of minimizing the total costs. Details about the model decision variable, model parameters, and model criteria are shown in Table 1, Table 2, and Table 3, respectively.

Table 1. Model decision variables.

Decision Variable	Description
xij	Takes, 1 if customer $j \in J$ is assigned to district $i \in I$, 0 therwise
yi	APLs that are located at district $i \in I$,
yIni	New APLs that are set up at district $i \in I$,
yOuti	APLs that are removed from district $i \in I$,
h1i	Auxiliary variable
h2i	Auxiliary variable

Table 2. Model parameters.

Parameter	Description
λ_k	Weight for criterion $k \in K$ in the multi-criteria objective function
c_{ij}	Assigment cost for customer $j \in J$ to an APL located at district $i \in I$
d_j	Customer $j \in J$ demanded
sc_i	Setting up cost for an APL located at district $i \in I$
dc_i	Reemoving cost for an APL located at district $i \in I$
uc_i	Upkeep cost for an APL located at district $i \in I$
m	APL capacity utilization minimum percentage
a_i	APL capacity at district $i \in I$
$b_{i,t\text{-}1}$	Previously existing APL located at district $i \in I$

Table 3. Costs criteria included in the multi-objective function.

Criterion	Description
$\sum_{\substack{i\in I \\ j\in J}} c_{ij}d_jx_{ij}$	Costs of assignment of all customers at all districts
$\sum_{i\in I} sc_i(yIn_i)$	Costs of setting up all new APLs at all districts
$\sum_{i\in I} dc_i(yOut_i)$	Costs of all decommissioning APLs at all districts
$\sum_{i\in I} uc_i(y_i)$	Costs of keeping all working APLs at all districts

Afterward, the FLP is defined as the following model (MC-CoAPL):
Minimize

$$\lambda_k Costs,\ k \in K : k > 0 \tag{1}$$

Multiple criteria objective function (Equation (1)) is equivalent to following mathematical formulation:

$$\lambda_1 \sum_{\substack{i\in I \\ j\in J}} c_{ij}d_jx_{ij} + \lambda_2 \sum_{i\in I} sc_i(yIn_i) + \lambda_3 \sum_{i\in I} dc_i(yOut_i) + \lambda_4 \sum_{i\in I} uc_i(y_i) \tag{2}$$

subject to

$$yIn_i = y_i - b_{i,t-1} + h1_i,\ \forall i \in I \tag{3}$$

$$yOut_i = b_{i,t-1} - y_i + h2_i,\ \forall i \in I \tag{4}$$

$$\sum_{i\in I} x_{ij} = 1\ ,\ \forall j \in J \tag{5}$$

$$Mx_{ij} \geq y_i\ ,\ \forall i \in I,\ \forall j \in J\ : i = j \tag{6}$$

$$\sum_{j\in J} d_j \geq m \sum_{i\in I} a_i y_i \tag{7}$$

$$\sum_{j\epsilon J} d_j x_{ij} \leq a_i y_i, \forall i \in I \tag{8}$$

$$x_{ij}\ \in \{0,1\}, \forall i \in I,\ \forall j \in J \tag{9}$$

$$y_i, yIn_i, yOut_i, h1_i, h2_i \in \mathbb{Z}^+,\ \forall i \in I \tag{10}$$

The multicriteria model (MC-CoAPL) is expressed in the Equation (1), compounded by the criteria described in the Table 3 making the Equations (2) and (3) to Equation (10) defines the constraints:

1. Equations (3) and (4) describe the APLs to set up and to retire, respectively. In these constraints, we use auxiliary variables for binding the equations.
2. Equation (5) make each customer $j \in J$ to be assigned to a district $i \in I$ only if an APL is there.
3. Equation (6) ensures that, if an APL is located in a district, then the customers in that district have to be assigned to it. Here, number M means a sufficiently large number.
4. Equation (7) guarantees a minimum APL use for a given demand.
5. Equation (8) ensure APLs capacities are not violated.
6. Equations (9) and (10) describe the variable ranges.

3.2. Agent-Based Simulation Model

The agent-based simulation model is constructed over customer *nodes* $j \in J = \{1, 2, 3, \ldots, J\}$, city district nodes $i \in I = \{1, 2, 3, \ldots, I\}$, and temporal set node $t \in T = \{0, 1, 2, \ldots, T\}$, the simulation model was constructed using an agent-based modeling technique. At time $t = 0$, the simulation begins with supplied initial numbers for the population, e-shoppers, APL users, and parcel requests. The districts serve as the basic agents in the simulation. As a result, each district $i \in I$ is referred to by the prior magnitudes. Following that, the population, e-shoppers, APL users, and parcel demands data are updated on a weekly basis.

$$population_{it} = population_{i,t-1}\alpha_{it}\epsilon, \forall i \in \mathrm{I}, \forall t \in T : t > 0 \quad (11)$$

$$eShoppers_{it} = eShoppers_{i,t-1} + \beta_{it}(population_{i,t-1} - eShoppers_{i,t-1})\epsilon, \forall i \in I, \forall t \in T : t > 0 \quad (12)$$

$$APLusers_{it} = APLusers_{i,t-1}\gamma_{it}\varphi_{it}\epsilon, \forall i \in I, \forall t \in T : t > 0 \quad (13)$$

$$parcelDemand_{it} = APLusers_{it}ppu_{it}\delta_{it}\epsilon, \forall i \in I, \forall t \in T : t > 0 \quad (14)$$

where α_{it} is a random variable that represents the city's historical population growth, and β_{it}, γ_{it}, and δ_{it} are the purchases per user, the APL users growth factor, and eShoppers growth factors, respectively, from time $t-1$ to t such that $\beta_{it} = \beta_{i,t-1}\epsilon$, $\gamma_{it} = \gamma_{i,t-1}\epsilon$, and $\delta_{it} = \delta_{i,t-1}\epsilon$,$\forall i \in I$, $\forall t \in T$:$t > 0$. Note that β_{it} variables have to be turned when $t = 0$ by dividing the real e-shoppers' yearly growth rate over the e-shoppers' share initial value. Random effects are represented by a uniform random variable, ϵ, in the interval [a,b], that is $\epsilon \sim \mathrm{U}[\mathrm{a}, \mathrm{b}]$. Moreover, φ_{it} denotes the impact on the parcel demand of APLs in a given district $i \in I$ at time $t \in T$. This effect is expressed as follows: $\varphi_{it} = 1 + \omega\frac{y_i}{\sum_{i \in I} y_i}$, $\forall_i \in I$, $\forall_t \in T\ : t > 0$, where ω is the sensitivity of increasing the number of APL users and y_i is the number of APLs available in district $i \in I$. Additionally, the purchases (Equation (15)) per APL user (ppu_{it}) are computed using the temporal demand distribution (dd_{t}) and the average purchases per year (ppy):

$$ppu_{it} = ppy\ \ dd_t, \forall_i \in I \quad (15)$$

Lastly, at the end of every month, the FLP solver process is run using the simulated data at that time. Later, the FLP solution feedbacks the simulation model by deciding the optimal location and number of APLs.

Above methodology has also been implemented by the authors in previous papers [11,12]. Authors have also founded similar approach for estimating eShoppers, APLs users, and parcel demand growth in paper [24] about case of APLs usage in Australia..

4. Results

4.1. Population

First, the results obtained regarding the population were analyzed. Initially, according to the information obtained, a population of 485,786 inhabitants was assumed. However, as the weeks of the simulation passed, the population increased. This is logical since, in the data, an initial growth rate in the population of 0.009 was also assumed. Therefore, the population will increase. Figure 1 shows population evolution over 3 years. Table 4 presents population results for each year of the simulation.

Table 4. Population results for each year of the simulation.

Year	Population
1	493,211
2	500,859
3	508,031

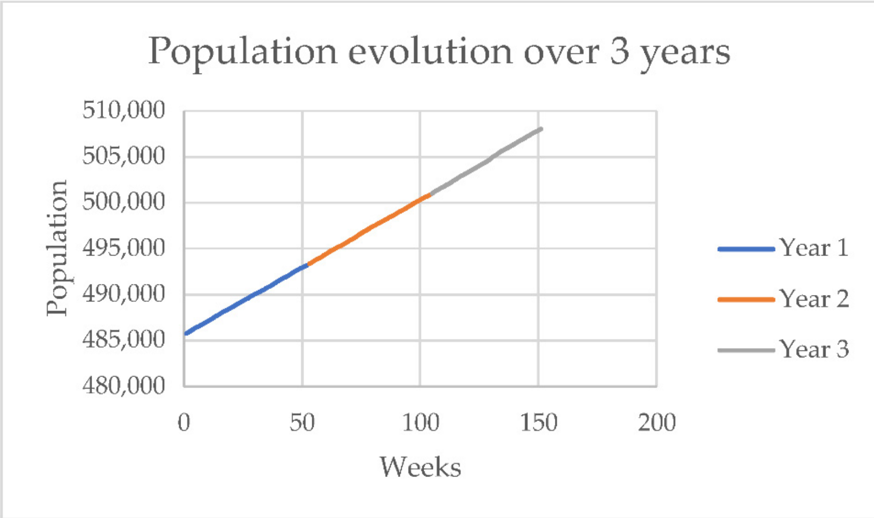

Figure 1. Population evolution over 3 years.

4.2. E-Shoppers

In the first place, e-shoppers are nothing more than those from the total population that buy online. Furthermore, due to the input data, it is known that they initially represented 64% of the population. Based on what is observed in the results, the initial number of e-shoppers was 310,903. In Figure 2 trend of e-shoppers evolution over 3 years is given. Figure 3 presents e-shoppers evolution rate over 3 years. Table 5 shows e-shoppers results for each year.

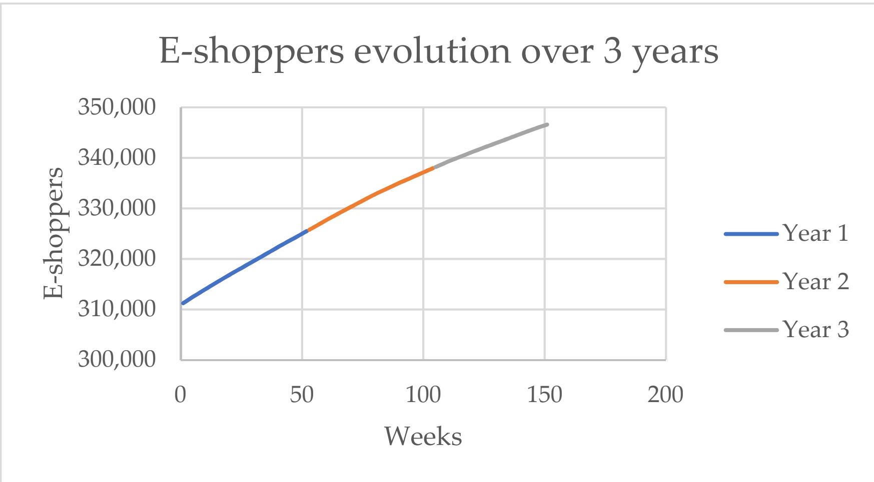

Figure 2. E-shoppers evolution over 3 years.

However, as defined before, the population increased with respect to the time of the simulation. Therefore, it was expected that the number of e-shoppers would also increase and that was exactly what was observed. However, it did not do so with the same ratio of 0.009 as the population did because it must be remembered that an e-shopper growth rate of 0.1 was also assumed in the input data. That was why the number of e-shoppers increased with respect to these two factors.

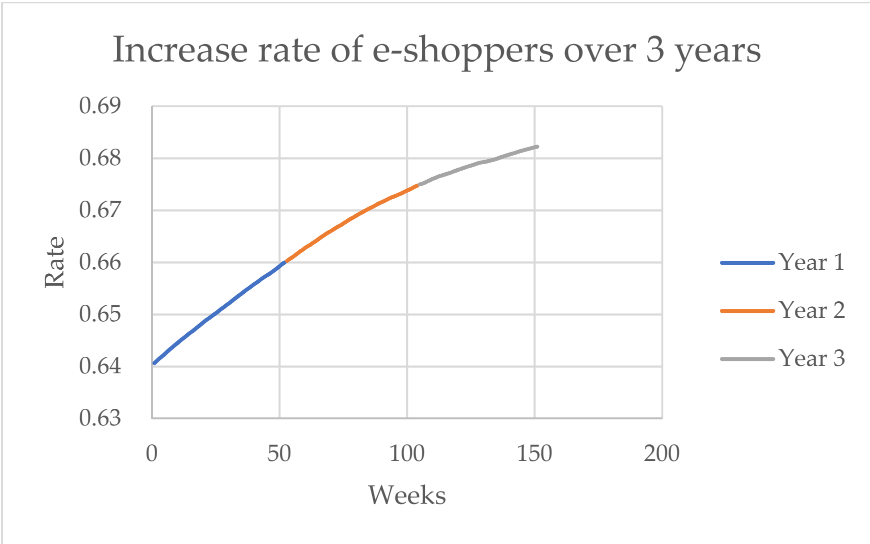

Figure 3. E-shoppers evolution rate over 3 years.

Table 5. E-shoppers results for each year.

Year	E-Shoppers	Rate
1	325,514	0.66
2	337,960	0.67
3	346,595	0.68

4.3. APL Users

APL users represent the number of people within the set of online shoppers who are willing to use lockers. Initially, they were 3.3% of e-shoppers because that was how it was defined in the data. Similar to the above, the APL users had their own growth rate defined in the input data and, therefore, evolved differently than the e-shoppers. In other words, they did not remain at 3.3% of e-shoppers, but the percentage increased. Figure 4 displays APL users evolution over 3 years. Figure 5 presents APL users evolution rate over 3 years. Table 6 shows APL users results for each year.

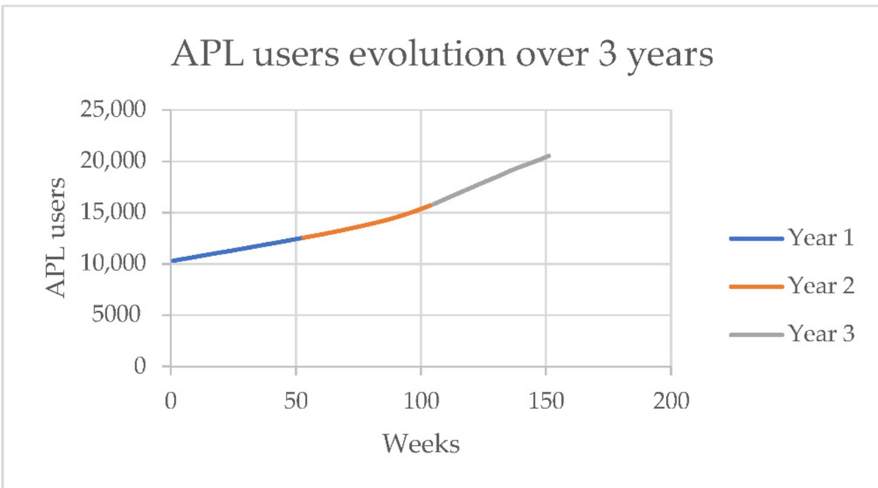

Figure 4. APL users evolution over 3 years.

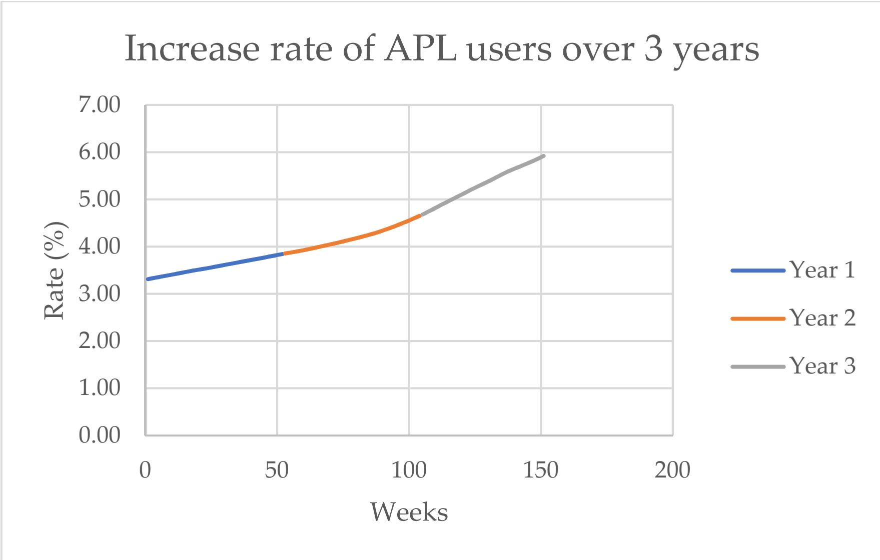

Figure 5. APL users evolution rate over 3 years.

Table 6. APL users results for each year.

Year	APL Users	Rate (%)
1	12,512	3.8
2	15,721	4.7
3	20,520	5.9

4.4. Demand Analysis

Figure 6 shows a weekly distribution of the demand obtained from company A. This data was introduced in the model and Figure 7 shows the results. Clearly, it can be observed how the shape of the demand in the results was exactly the same as expected. That is, every year followed the expected demand, where the months before Christmas were the ones with more demand, mainly because it is in this period when more online purchases occur. However, it must be taken into account that since there was also an increased rate in the demand, the demand did not remain stuck; although the shape was maintained, it grew every year.

Figure 6. Weekly forecast of the expected demand.

Figure 7. Weekly evolution of the demand over 3 years.

4.5. Year Analysis

These results can be analyzed as follows. First, it can be seen that the facility location problem was solved for the first year, with an average of 41 lockers to cover an average demand of 12,931 orders per year. Regarding the opening and closing costs, these were EUR 166,600 and EUR 1280, respectively. Note that the opening costs were high in comparison with the other years and that was because the simulation started from scratch when lots of APLs needed to be opened. Considering that starting a new locker cost EUR 2450 and decommissioning it cost EUR 80, it could be calculated that in this first year, 68 APLs were installed and 16 were closed, ending the year with 52 lockers. On one hand, the upkeep costs were EUR 330,460, which represented the maintenance costs of the average value of 41 lockers this first year; that is, 155 EUR/locker/week, with 52 weeks the first year. On the other hand, the service costs were 93.37% of the EUR 7,019,279 total costs, which were, by far, the most expensive costs. Table 7 presents overall analysis for each year. Figure 8 shows percentage breakdown of the total costs for the first year (a), percentage breakdown of the total costs for the second year (b), and percentage breakdown of the total costs for the third year (c).

Table 7. Overall analysis for each year.

Year	Number of Lockers	Average Number of Lockers	Opening Costs	Closing Costs (EUR)	Upkeep Costs (EUR)	Service Costs (EUR)	Total Costs (EUR)	Average Demand	Demand Increase w.r.t. Last Year
1	52	41	166,600 (2.21%)	1280 (0.02%)	330,460 (4.40%)	7,019,279 (93.37%)	7,517,619	12,931	-
2	77	60	85,750 (0.80%)	800 (0.01%)	482,050 (4.49%)	10,162,552 (94.70%)	10,731,152	19,000	47%
3	122	91	139,650 (0.89%)	960 (0.01%)	662,005 (4.24%)	14,802,174 (94.86%)	15,604,789	28,678	51%

In the second year, an increase of 47% in the demand was predicted. This was in agreement with what occurred in practice, where the average number of lockers changed from 41 to 60, which was also a rise of 47%. The opening costs for this year were EUR 85,750, which meant that 35 new APLs were opened, whereas 10 lockers were closed, leading to EUR 800 of decommissioning costs. The final balance of lockers ended up being 77 APLs for the second year of the simulation. The upkeep costs for this year represented the maintenance cost of the average number of 60 lockers, specifically, EUR 482,050. Finally, once again, the service costs were where most of the money was spent, namely, 94.70% of the EUR 10,731,152 of the total costs.

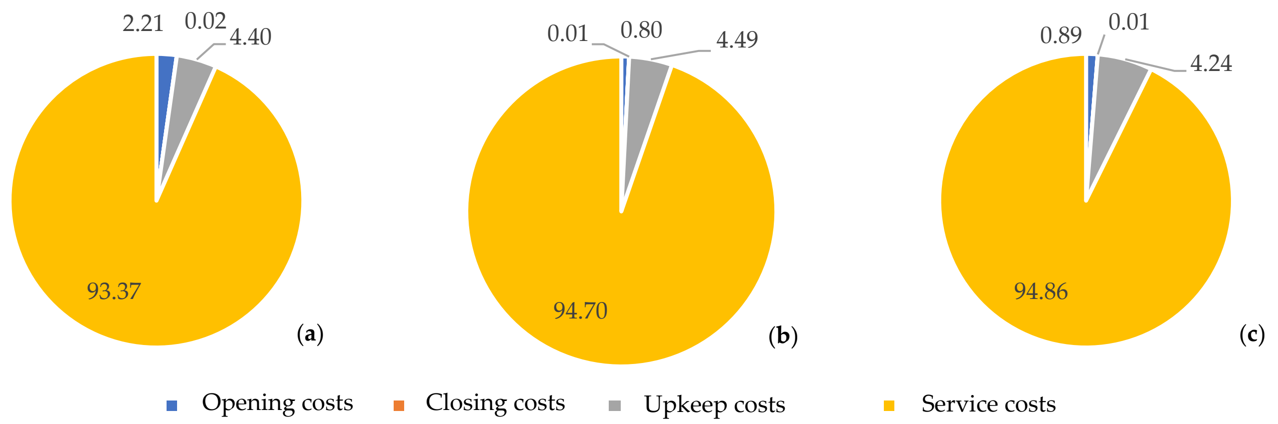

Figure 8. (**a**) Percentage breakdown of the total costs for the first year. (**b**) Percentage breakdown of the total costs for the second year. (**c**) Percentage breakdown of the total costs for the third year.

Finally, the third year of the simulation did not show any surprise relative to past years. The average demand increased by 51% and the average number of lockers increased in the same way, with a rise of 52%. To cover this new demand, 57 new lockers were created and 12 removed, involving EUR 139,650 of opening costs and EUR 960 of decommissioning costs. This led to 122 APLs at the end of the simulation. Since the average number of lockers was greater, there were higher upkeep costs. Once more, the service costs were the highest expenses of the year, being 94.86% of the EUR 15,604,789 of the total costs.

5. Discussion

A standard scenario was selected to test the multi-criteria simulation-optimization model. Thus, this work proposed the use of utilizing optimization and simulation together to deal with automated parcel locker (APL) network. On the one hand, the multiple criteria simulation-optimization model is based on agent-based modelling and evaluates the evolution of the population, eShoppers, APL users, and parcel demand. On the other hand, the optimization model decides the number and location of APLs through a multi-objective facility location problem (MOFLP). Thus, the system establishes the link between the outputs of one model and the other one. In this case, standard scenarios were examined for a variety of growth levels of APL users and the vulnerability of eShoppers to become APL users once there is an APL adjacent.

6. Conclusions

A list of conclusions was drawn after the analysis of the results.

Conclusion 1. Costs and suggested number of lockers: Firstly, our research findings indicate that there will be an increase in population, eShoppers, APL users, parcel demands, and number of APLs for the coming years in the city of Poznań in Poland, considering a realistic standard scenario for it.

Conclusion 2. Enhancement of simulation-optimization methodology: This paper encourages the use of the methodology to combined simulation and optimization to deal with complex real world problems. In practice, complex systems require a combination of methodologies that are capable of easily dealing with a problem.

Conclusion 3. What makes this study significant is that the experimentally observed increase in online sales, which was a phenomenon that was already intuited in the initial stages of the study, was also predicted via simulations. Forecasts on the evolution of e-shoppers, APL users, and demand were made possible thanks to data from company A and the agent-based simulation-optimization model. As a result, it is possible to graph the data and see how an increase is likely to occur.

Conclusion 4. However, when comparing the real locker data with the simulation results, there was a disparity. As previously stated, this was owing to the fact that the demand data for APL users provided by company A was for a 5-year estimate; however, the project only simulated 3 years. Nevertheless, the fact that company A is currently overpopulating Poznań with APLs has shown itself to be an effective medium-to-long-term plan. The reason for this is that they purchased more lockers than needed at a period when demand was low in order to save money when demand increased.

On the one hand, the mathematical model operation was tested and verified. As expected, the number of lockers available was directly proportional to the demand at any given time. Thus, the model's key benefit was that it experimentally demonstrated that the facility location problem was handled with cost optimization and demand coverage. In addition, the model allowed for a breakdown of costs.

Conclusion 5. In terms of expenses, it should come as no surprise that a larger number of lockers entailed a higher cost. It should be noted that the expenses of opening and closing lockers were not totally accurate because decisions to act on lockers were not made on a daily basis, but rather took time. Service costs were the most significant component of the total expenditures, followed by maintenance costs. This is somewhat logical because they were weekly fees that were also dependent on the number of lockers, and thus, having more APLs means paying more.

Nevertheless, our APL simulation-optimization model has some limitations that may compromise the generalization of the results and conclusions here exposed. On the one hand, the model is highly data dependent. It means that results are heavily sensitive to initial data estimations. On the other hand, the multi-criteria optimization model is only able to capture relevant and actual information. Therefore, solutions coming from decision makers' subjective or descriptive analysis are unreachable from our methodology. This also considers the inclusion of additional criteria and the assigned weights in the multi-criteria approach.

The future work aims to cover the weaknesses previously described. Firstly, data collection and/or estimation refinement is the clearest way of improving APL network works. Therefore, higher quality data and the consideration of advanced statistical methods in order to better describe the parcel demand patterns is our next step. Secondly, the use of additional cities, from different countries, will give some insights APL network determinants and how culture-related factors affect to online demand and the use of APLs. Finally, a deeper integration of the simulation-optimization framework, with even higher interdependencies between both models is also of great interest for Operations Research scholars and practitioners.

To summarize, it was stated that there is still a major difficulty in the world of deliveries, namely, the last-mile delivery problem. APLs are used as a favourable alternative among all available solutions that, with proper optimization, can be the solution to the problem. Of course, it should be kept in mind that this is still a relatively new area and that there is still work to be done.

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