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EVALUATING THE EFFICIENCY OF A PARCEL LOCKER NETWORK: A CASE STUDY OF VARIABLE DEMAND AND STORAGE DURATION IN PARDUBICE CITY

Summary. *Last-mile delivery is the last element of the supply chain. It plays a key role in urban logistics processes related to the efficient and environmentally friendly transportation of goods within an urban area. The growth of e-commerce, the need to minimize the environmental impact of transportation, and the increasing demand for efficient delivery services require alternatives to traditional home delivery. Numerous studies suggest that the use of parcel locker networks helps optimize transportation and reduce logistics costs. This method is simple to implement, although it requires additional investment in parcel lockers and support from delivery service customers. This study examines the operation of a parcel locker network under conditions where users have up to three days to collect their parcels after delivery, considering variable demand for parcel locker deliveries depending on the day of the week. Locker occupancy was calculated for different user behavior scenarios, particularly cases where different shares of recipients pick up their parcels on the first or second day after delivery. The calculations were based on data from Pardubice, Czech Republic (a city with a population of 92362 inhabitants). The findings indicate that if a significant share of consumers delays the parcel collection, the existing network may not be sufficient, leading to delivery bottlenecks. The findings can be used to improve parcel locker network management and enhance last-mile logistics efficiency. To address capacity shortages, potential solutions include limiting parcel storage time instead of immediately expanding locker networks. However, further research and user feedback are needed to validate this approach.*

Key words: *last-mile delivery, parcel locker, parcel flow, modeling.*

1. INTRODUCTION

The growth of e-commerce has led to an increasing demand for the delivery of goods to retail consumers. The global parcel delivery volume surged from 36 billion parcels in 2013 to 161 billion parcels in 2022 [1]. According to forecasts, this figure is expected to reach 256 billion parcels by 2027 [1].

In addition to the increasing volume, last-mile delivery faces rising demands for faster delivery, reduced environmental impact, and challenges associated with an aging workforce [2]. Consequently, the share of last-mile delivery costs in the total delivery cost has been increasing: in 2018, it accounted for 41 %, whereas by 2023, it had risen to 53 % [3].

In general, two main last-mile delivery methods can be distinguished: address delivery (home/office) and customer pick-up at a secondary location (collection points, parcel lockers, "Click and Collect" services).

Parcel locker (PL) delivery offers advantages to delivery service providers and recipients. For logistics providers, shipment consolidation significantly reduces the number of delivery points. This simplifies the

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process of optimizing delivery routes, reduces time spent on delivery, and ultimately leads to cost savings [4]. Another advantage of parcel locker delivery is eliminating (or significantly reducing) the risk of a second trip due to failed deliveries (e.g., when the recipient is not home).

Cost savings can also benefit recipients, as parcel locker delivery fees are typically lower than those for home courier delivery [5]. Additionally, the lack of a need to synchronize one's availability at home with the courier's arrival time is another key advantage of using parcel lockers.

The World Economic Forum, in its report, suggests (based on its research and modeling) the six most effective measures that will help improve the delivery ecosystem in cities. One of these measures is using a network of pick-up points for delivery, which can reduce the number of delivery trips by up to 15 % and the cost of deliveries by up to 15 % [6].

2. STATEMENT OF THE PROBLEM AND RELEVANCE OF THE STUDY

Analyzing the concept of organizing last-mile delivery using parcel lockers, Michael Kahr, in his work [7], highlights the following advantages:

- possibility of delivering several shipments at a stroke (increasing delivery capacity without increasing the number of couriers);
- cheaper and legally simpler than using autonomous vehicles;
- environmental friendliness;
- supporting physical distancing (this parameter is critical during epidemics, which was especially evident during the Covid-19 pandemic);
- 24/7 availability;
- suitable for use in most climatic and geographical conditions;
- can be powered by batteries or solar panels;
- parcel lockers are easy to build and maintain;
- their location can be easily changed if necessary.

According to Statista, parcel delivery to lockers is gaining popularity in many European countries. Table 1 presents data from surveys conducted during 2023–2024.

Table 1

Popularity of delivery to parcel lockers in European countries (according to Statista portal)

Country	Popularity level	Using self-service parcel terminal as a delivery method for online purchases, %	Source
Finland	the most popular	80	https://www.statista.com/statistics/1428638/preferred-methods-of-delivery-finland/
Poland	the most popular	82	https://www.statista.com/statistics/958978/poland-e-commerce-delivery-methods/
Slovakia	second (after home delivery)	21	https://www.statista.com/statistics/1375157/slovakia-location-of-package-delivery/
Croatia	the second (after home delivery)	47	https://www.statista.com/statistics/1446097/croatia-e-commerce-delivery-preferences/
Estonia	the most popular	83	https://www.statista.com/statistics/1373858/top-e-commerce-delivery-locations-estonia/
Lithuania	the most popular	76	https://www.statista.com/statistics/1374440/top-delivery-locations-among-e-shoppers-lithuania/
France	the second (after home delivery)	71	https://www.statista.com/statistics/383007/leading-e-commerce-delivery-methods-used-in-france/
Latvia	the most popular	69	https://www.statista.com/statistics/1373938/top-e-commerce-delivery-locations-latvia/
Romania	the second (after home delivery)	32	https://www.statista.com/statistics/1483384/romania-delivery-place-preference/

In the Czech Republic, 318.7 million parcels were delivered in 2024 [8], averaging 0.87 million daily parcels. However, considering fluctuations in delivery demand depending on the day of the week (workday/weekend) or seasonal variations, the number of deliveries on a given day can be significantly higher. Therefore, the efficient organization of these deliveries is a crucial issue for the country.

Parcel locker delivery, as a means of shipment consolidation and optimization of delivery routes and schedules, is seen by logistics service providers as an effective alternative despite the need for additional investments in infrastructure [9].

According to surveys in the Czech Republic (Behavio Labs, March 2023), the answers to the question "Where do you prefer to have your packages delivered to?" were distributed as follows [10]:

- home/work: 44 %;
- pick-up point: 28 %;
- pick-up box (PL): 21 %;
- in-store pick up: 7 %.

According to similar surveys conducted by DHL in 2022, 17 % of respondents chose parcel locker delivery, while in 2024, this share increased to 33 % [11, 12]. This indicates the growing popularity of parcel lockers among the Czech population.

This study aims to assess the adequacy of the parcel locker network in Pardubice in meeting last-mile delivery demand under different scenarios and to examine the impact of consumer behavior regarding parcel pick-up speed on the capacity of the parcel locker network.

In line with this objective, the following tasks are defined:

- conduct a literature review on last-mile delivery research involving parcel lockers;
- analyze current trends in last-mile delivery demand in Pardubice throughout the week;
- based on actual demand data for last-mile delivery in Pardubice, calculate parcel locker network performance parameters depending on consumer behavior.

3. ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Scientific papers on the study and optimization of the last-mile delivery process using a network of parcel lockers can be divided into two groups:

- parcel locker service and parcel lockers` network design problem;
- research individual delivery indicators to parcel lockers based on real examples.

In the study [4], the authors developed a parcel delivery routing model between the central depot and destination parcel lockers, considering vehicle load capacity, locker capacity, and time constraints. Their findings indicate that allowing recipients to specify multiple (up to three) alternative delivery points can significantly reduce delivery time and costs due to increased flexibility. In the study [13], the authors proposed a two-tier parcel delivery network model to address routing problems between depots and parcel lockers and to determine the optimal placement and size. The issue of parcel locker network design was also the focus of the study [14], where the authors developed a mathematical model to find optimal integrated decisions regarding parcel locker locations and the number of PL units. The authors of [15] also address the problem of optimal parcel locker placement, with the optimization criterion maximizing the overall service level while considering customer preferences. In [16], a multi-objective optimization problem is used to determine the optimal locations of PL units, incorporating three objectives: maximum coverage, minimum overlap, and minimum total idle capacity. In [17], using a mixed-integer programming model, the authors argue that mobile lockers are an efficient solution for ensuring short walking distances and long overlap times for parcel retrieval without requiring excessive investment in a network of stationary parcel lockers. Research published in [18] also examines the problem of determining the optimal PL capacity but with the objective of cost minimization. The authors consider delivery demand fluctuations over the week, month, and year.

According to the research, the main parameters that allow us to assess the effectiveness of the last-mile delivery network are time, cost, and user acceptance (Table 2).

Table 2

Research on parameters affecting the efficiency of last-mile delivery using a parcel locker network

Authors	Research methods	Investigated parameter	Main results	Research environment
Van Duin et al., 2020 [19]	cost effectiveness analysis, multi-criteria analysis, simulation modeling	number of stops for the delivery route, daily delivery costs	68 % fewer stops, 16 % less delivery costs	Amsterdam (The Netherlands)
Hofer et al., 2020 [20]	panel survey	estimation of reduced vehicle kilometers and reduced emissions based on symmetric activity chains	maximum distance to the PL at which users use environmentally friendly methods of transportation is 1.9 km	Graz (Austria)
Mitrea et al., 2020 [21]	survey	the adoption of PL, travel time to PL for people	the adoption depends on demographic factors; the most acceptable time to pick up a parcel is up to 10 minutes (72 %)	Turin (Italy)
Kim & Wang, 2022 [22]	descriptive analysis, discrete choice modeling	the adoption of PL, the maximum tolerable distance to PL for people	the tolerable distance is not associated with delivery frequency but varies by demographic factors (gender, age, residential type, and employment status)	New York (The U.S.A.)
An et al., 2022 [23]	survey, structural equation modeling	the adoption of PL	technological efficacy could be a more appealing component than protection motivation in consumers' adoption	The U.S.A.
Ranjbari et al., 2023 [24]	field observations, difference-in-difference (DiD) method in a pre-test/post-test control group design (comparing delivery to a building with a parcel locker and to a building without a PL)	delivery time	average time spent by courier inside the building decreased by 50–60 %	Seattle (The U.S.A.)
Cieśla, 2023 [25]	survey, Kano model	service attributes	defining quality attributes that are mandatory for service providers to ensure the population perceives PL	Silesian Metropolis (Poland)
Ozyavas et al., 2025 [26]	branch-and-price algorithm	cost – environmental impact	increasing the density of the parcel locker network will help reduce the number of trips	Groningen (The Netherlands)

Based on the analysis of available statistical data, field studies, or population surveys, scientific literature examines public attitudes toward parcel locker delivery and the factors determining the efficiency of parcel lockers for both users and logistics operators. Practical case studies confirm theoretical findings that parcel locker delivery, compared to home delivery, leads to lower delivery costs, is more environmentally friendly, and helps reduce the number of trips within urban areas [19, 20, 24, 26]. A key

issue is determining the optimal density of the parcel locker network. On one hand, the distance to a parcel locker should be acceptable for users. On the other hand, an overly dense network may reduce the cost-saving effect of shipment consolidation and the reduction in delivery points.

Various factors can influence public attitudes toward parcel lockers. In [25], 21 factors were analyzed. Five key factors were identified as the most important for the population: 1) adjusting the size of the package to the size of the box (incorporating compartments of different sizes into the overall parcel locker module); 2) dedicated applications; 3) improvements for people with disabilities; 4) parcel locker location; 5) placing the parcel in a specific box (preference for lower compartments, up to 1.5 meters in height). Understanding these factors can help stakeholders develop and improve parcel locker services as a last-mile delivery solution. However, it is essential to consider that local conditions may influence the relative importance of these factors.

4. RESULTS AND DISCUSSION

4.1. Calculation of the capacity of the parcel lockers` network in Pardubice City and assessment of demand for delivery to a parcel locker

Pardubice is the capital city of the Pardubice Region in the Czech Republic. The area of Pardubice is 82.66 km^2, and the population is 92362 inhabitants (Czech Statistical Office). The density of the population is 1117 persons/km^2. The primary parcel delivery services in the city that provide delivery to parcel lockers are DPD, PPL, Zasilkovna, GLS, and Česká pošta. In addition, a significant share of parcel flows is from the e-shop ALZA, which has its delivery service and a network of parcel lockers.

Logistics providers provided data on the daily number of parcels delivered within Pardubice over one month. The available data included the delivery date, postal code of the delivery area, and parcel weight. Based on this information, the data were sorted by weight, and further analysis was conducted using only parcels weighing up to 10 kg. This weight limit is not precise, as parcel lockers have weight and size restrictions. However, since parcel size data were unavailable, a 10 kg weight limit was chosen for cases where parcels might meet the weight requirement but exceed the size limit for parcel locker delivery. In total, 157347 parcels were delivered across the city during the month, 7 % of which exceeded 10 kg. Fig. 1 presents graphs showing the variation in the number of parcel deliveries throughout the days of the week.

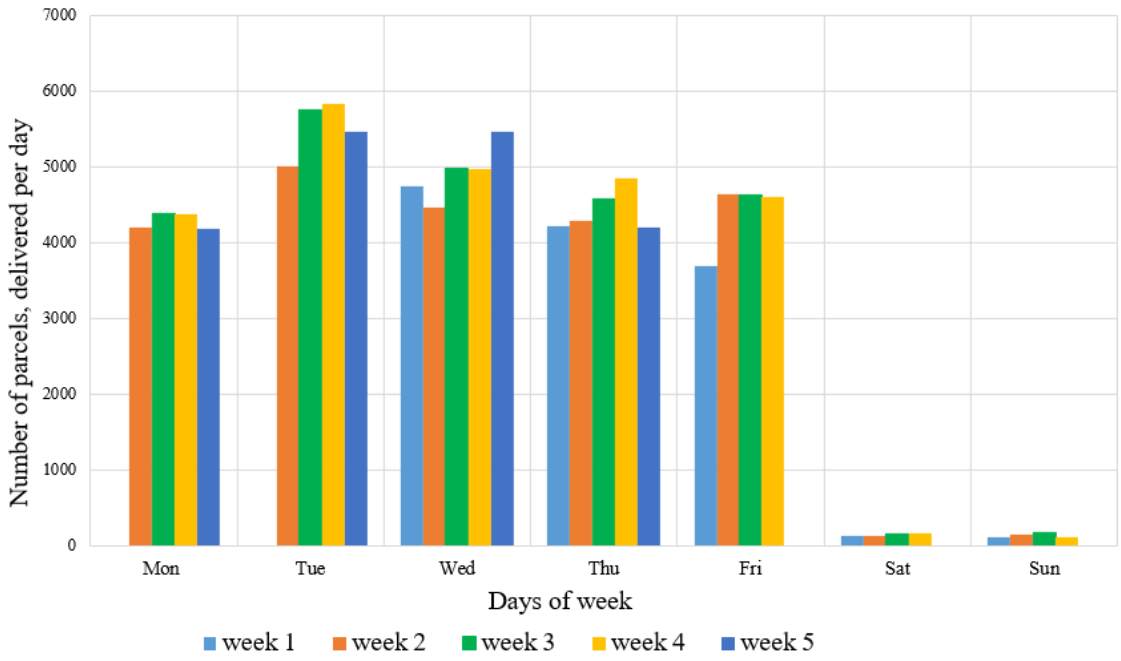


Fig. 1. Number of delivered parcels weighing up to 10 kg in Pardubice

The overall trend remains consistent across all observed weeks: the highest number of parcel deliveries occurs on Tuesdays, while deliveries drop sharply over the weekends. Table 3 provides a summary of the delivery volume statistics.

Table 3

Statistical data on the volume of parcel deliveries weighing up to 10 kg in Pardubice

Day of the week	The average number of delivered parcels	Standard deviation, parcels	Standard error of the means, parcels	Relative standard error, %
Monday	4287	108	54	1.26
Tuesday	5514	377	188	3.42
Wednesday	4928	369	165	3.35
Thursday	4429	277	124	2.80
Friday	4392	466	233	5.31
Weekend	735	24	8	1.07

As of early 2025, there were 60 parcel lockers in Pardubice, totaling 4310 compartments. The size of lockers varied, ranging from 10 to 190 compartments per unit. The density of parcel lockers through the city and their total capacity is uneven (Fig. 2). The postal code areas 53002 and 53003 have a total locker capacity exceeding the average daily parcel delivery volume. In contrast, the postal code area 53353 has no parcel lockers.

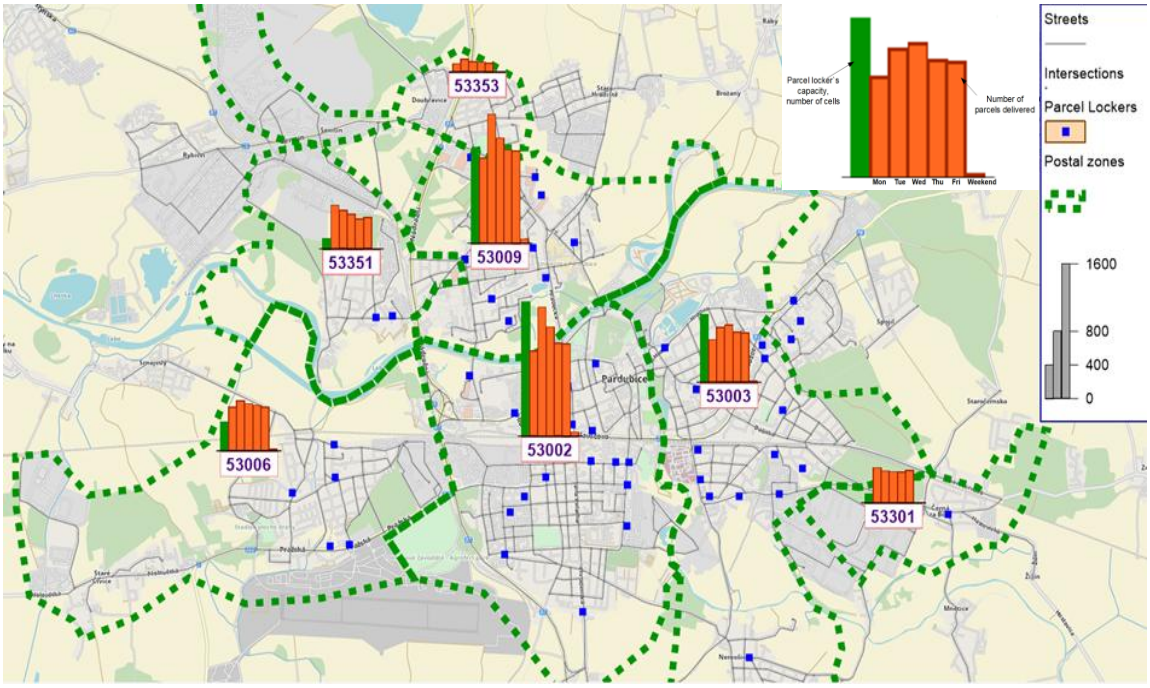


Fig. 2. Division of Pardubice into districts by postal codes and characteristics of parcel lockers' capacity and parcel delivery volumes (≤10 kg) in each district

According to the survey results published in [27], 35 % of respondents rated parcel locker delivery as "very convenient" and another 20 % as "convenient". According to [10], 21 % of respondents chose the "pick-up box" option as their preferred place for receiving their packages.

4.2. Describing the parcel locker operation model

Most last-mile delivery logistics operators operating in the Czech Republic (and Pardubice in particular) limit the storage period of a parcel in a parcel locker to three days. Therefore, further analysis is

conducted considering this restriction. Additionally, calculations are performed under the assumption that the average percentage of parcels collected on the first, second, and third day after delivery remains stable.

Fig. 3 shows a diagram of filling a parcel locker with parcels where:

- N_i – number of parcels delivered by the logistics operator to the parcel locker on the day i, parcels/day;
- x_1 – parcels picked up by users on the day of delivery to the parcel locker, share of this day`s delivery;
- x_2 – parcels picked up by users on the second day after delivery to the parcel locker, the share of parcels left from the first day.

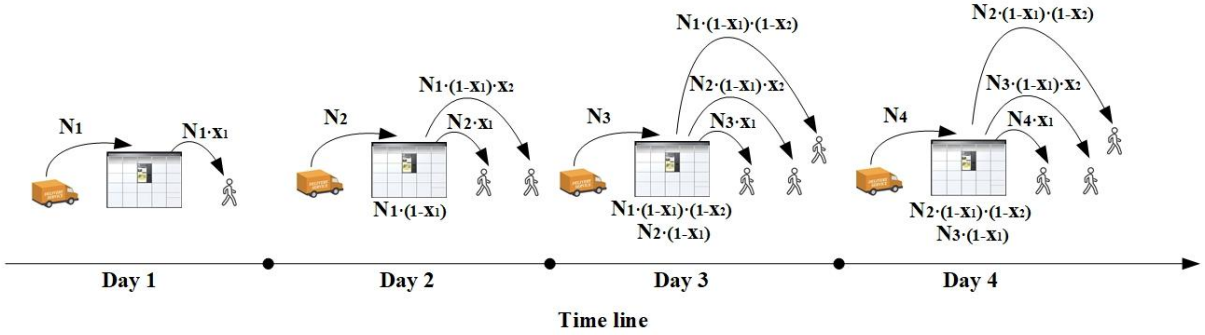


Fig. 3. Scheme of the parcel locker operation

On the first day, a batch of parcels (N_1) is delivered to the parcel locker, where this number does not exceed the locker's capacity. Throughout the day, customers collect a portion of these parcels (x_1), where the fraction of collected parcels can range from 0 to 1 (100 %). On the second day, a new batch of parcels (N_2) arrives at the parcel locker. Since some parcels from the first day remain uncollected ($N_1 \cdot 1-x_1$), the value N_2 cannot exceed the difference between the locker's capacity and the number of uncollected parcels. During the second day, customers collect another portion of parcels delivered on the first day (x_2) and a fraction of the parcels delivered on this day (x_1). On the third day, another batch of parcels (N_3) is delivered. At this point, some parcels from the first day ($N_1 \cdot 1-x_1 \cdot 1-x_2$) and some from the second day ($N_2 \cdot 1-x_1$) remain in the locker. During the third day, customers collect the remaining parcels from the first day, some from the second day, and a fraction of the newly delivered third-day parcels. In general, on any randomly chosen weekday, the parcel locker operates under the scheme of day 3 (according to the markings in Fig. 3).

4.3. Modelling the capacity of the parcel lockers` network

Based on the above information and considerations, an assessment of the capabilities of the existing parcel lockers` network in Pardubice was carried out for three scenarios:

- 21 % of all parcels weighing up to 10 kg are delivered to parcel lockers (based on [10]);
- 35 % of all parcels weighing up to 10 kg are delivered to parcel lockers (based on [12, 27]);
- 50 % of all parcels weighing up to 10 kg are delivered to parcel lockers (future increase in PL delivery share).

The calculation was performed for changes in values x_1 (parcels picked up by users on the day of delivery to the parcel locker, share of this day`s delivery) from 0 to 100 % in 10 % increments and for changes in values x_2 (parcels picked up by users on the second day after delivery to the parcel locker, the share of parcels that were left from the first day) from 0 to 100 % in 10 % increments.

In the first scenario, regardless of the combination of parcel pickup shares on the first and second day, the system operates without overloads, meaning the total capacity of the parcel lockers is sufficient to accommodate the parcels.

When 35 % of the total parcel flow is delivered to parcel lockers, a capacity shortage begins to arise when fewer than 20 % of consumers pick up their parcels on the day of delivery and, at the same time, fewer than 10 % of the parcels from the first day are collected on the second day.

More detailed calculation results for the case where 50 % of all parcels weighing up to 10 kg are delivered to parcel lockers are presented in Fig. 4, Fig. 5.

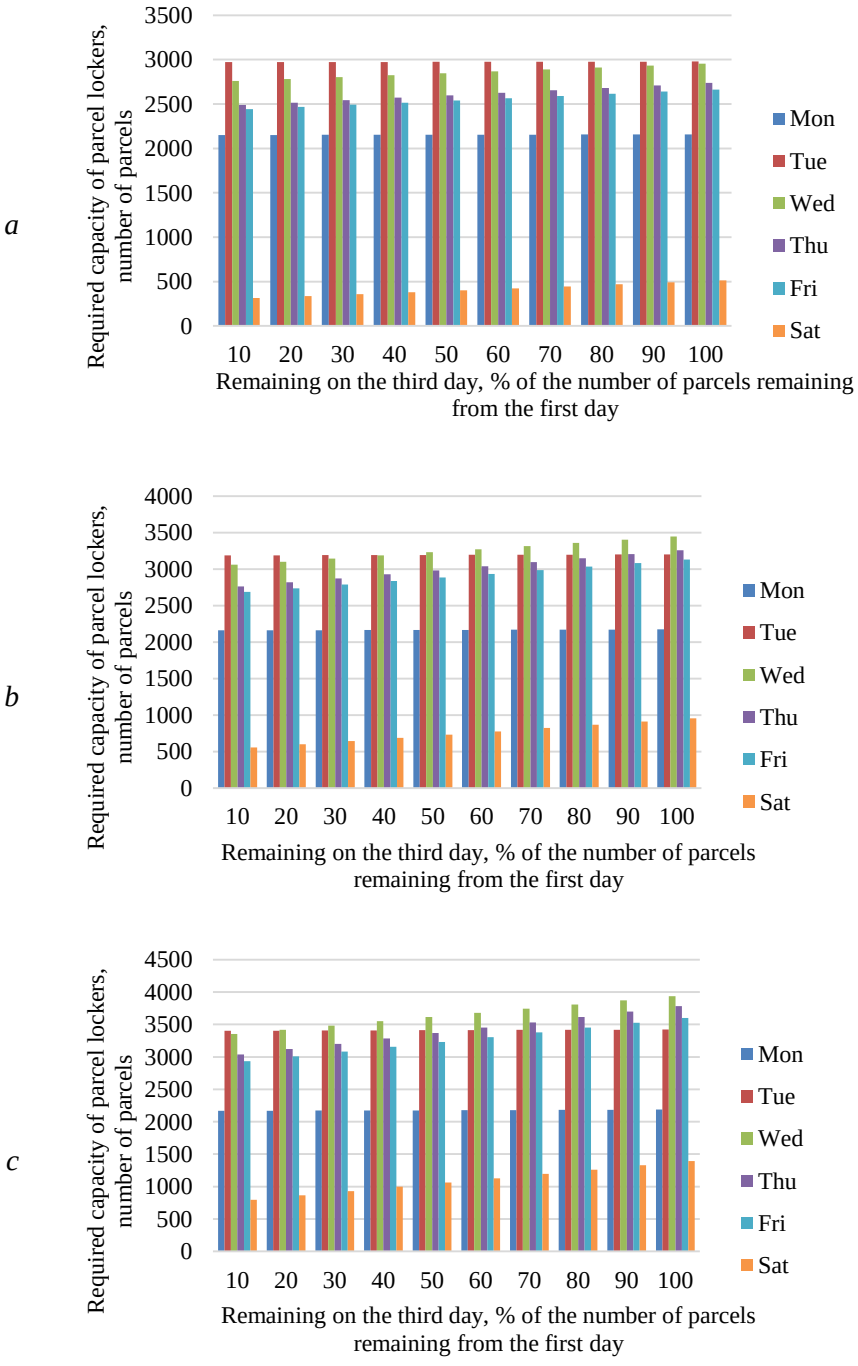
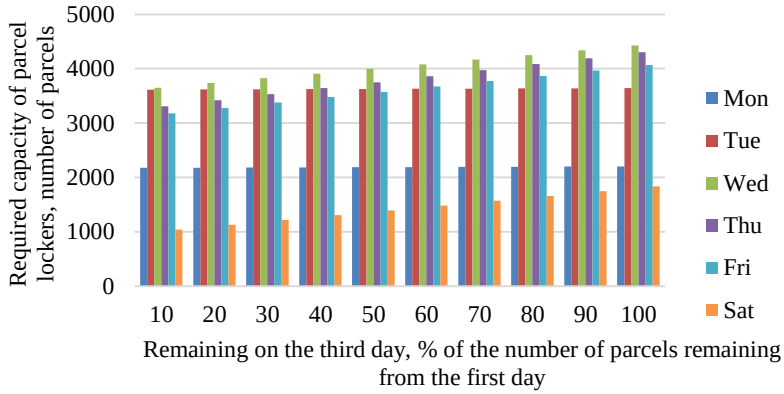
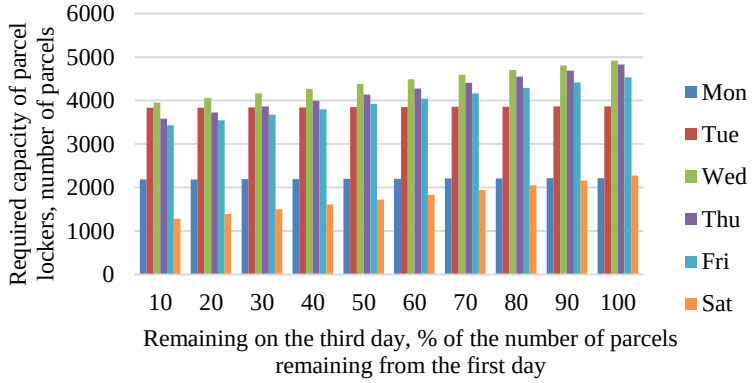


Fig. 4. Changes in parcel lockers` capacity requirements due to variations in consumer behavior regarding parcel pickup: a – x_1=90 %; b – x_1=80 %; c – x_1=70 %.

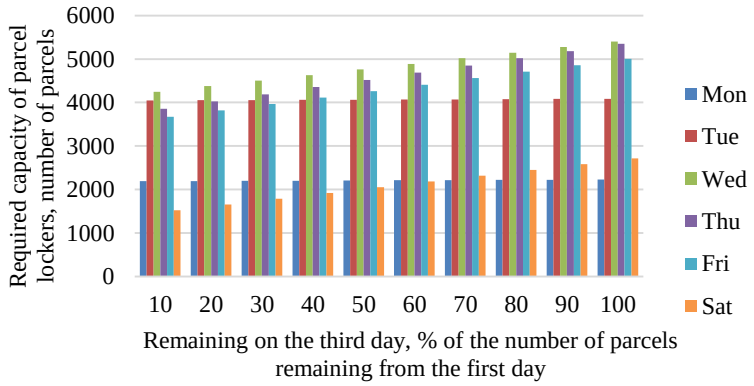
a



b



c



d

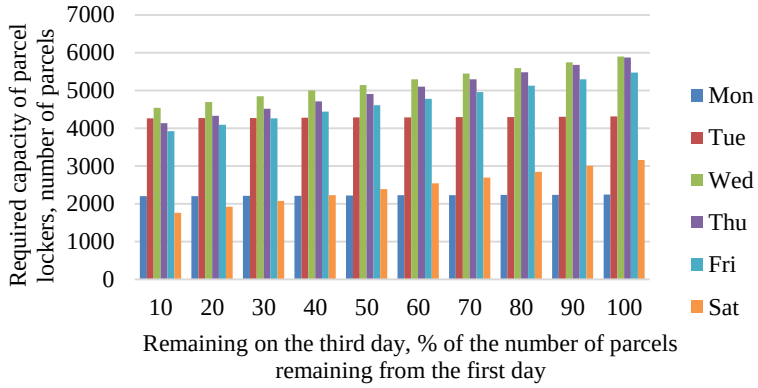
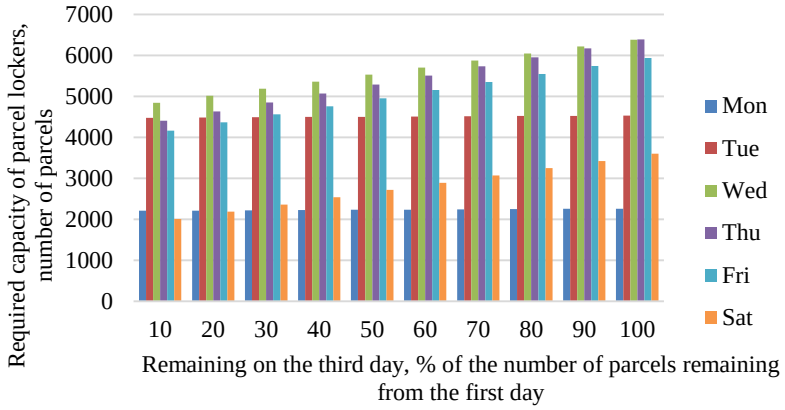


Fig. 5. Changes in parcel lockers` capacity requirements due to variations in consumer behavior regarding parcel pickup (parcel lockers` capacity = 4310 parcels): a – x_1=60 %; b – x_1=50 %; c – x_1=40 %; d – x_1=30 %.

e



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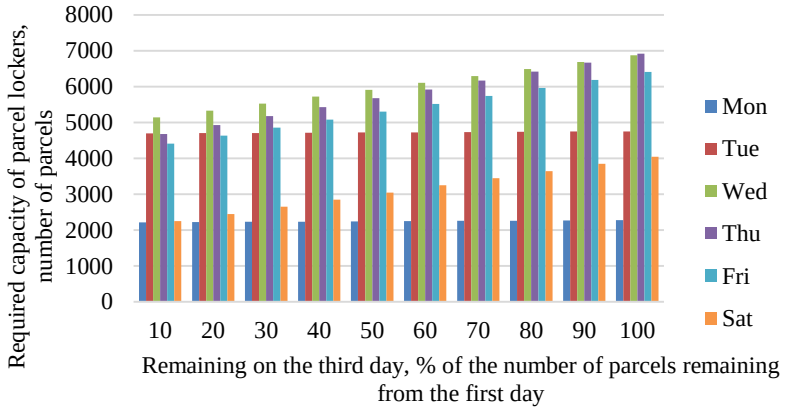

Fig. 5. (Continuation). Changes in parcel lockers` capacity requirements due to variations in consumer behavior regarding parcel pickup (parcel lockers` capacity = 4310 parcels): e – x_1=20 %; f – x_1=10 %.

The first instances of insufficient parcel locker capacity occur when fewer than 60 % of consumers pick up their parcels from the locker on the first day of delivery. At the same time, fewer than 10 % of the parcels from the first day are collected on the second day. A shortage of available lockers is observed on Wednesday.

When fewer than 50 % of consumers pick up their parcels on the first day of delivery, the threshold value x_2 is 50 % (a shortage of available lockers is observed on Wednesday). When it reaches 70 %, the shortage occurs on both Wednesday and Thursday; when $x_2 \leq 10$ %, it extends to Wednesday, Thursday, and Friday.

When fewer than 40 % of consumers pick up their parcels from the locker on the first day of delivery, a shortage of available lockers on Wednesday occurs at $x_2 = 80$ %. At $x_2 \leq 50$ %, the shortage exceeds 10 % (at $x_2 = 50$ % it reaches 10.5 % or 451 compartments, and at $x_2 = 0$ % it increases to 25.4 % or 1094 compartments). On Thursday, a shortage occurs at $x_2 = 60$ %, and at $x_2 = 30$ % it exceeds 10 %, reaching 24 % at $x_2 = 0$ %. When $x_2 \leq 10$ %, the shortage of available compartments in PL more than 10 % is also observed on Friday.

In the case when fewer than 30% of consumers pick up their parcels from the locker on the first day of delivery, the total parcel locker capacity will be insufficient to accommodate all parcels on Wednesday, regardless of the value x_2. A shortage will occur on Thursday at $x_2 = 90$ %, and on Friday at $x_2 = 60$ %. The maximum shortage of available locker spaces (in case when $x_2 = 0$ %) is 36.7 % (1584 compartments) on Wednesday, 36 % (1559 compartments) on Thursday, and 26.9 % (1661 compartments) on Friday.

In the case where fewer than 20 % of consumers pick up their parcels from the locker on the first day of delivery, a shortage of available locker spaces is observed on Tuesday, Wednesday, and Thursday, regardless of the value x_2, and on Friday when the value reaches $x_2 \leq 90$ %. The percentage of locker's compartments shortages varies from 3.9 % to 5.1 % on Tuesday, from 12.3 % to 48.1 % on Wednesday, from 2.2 % to 48.3 % on Thursday, and from 1.2 % to 37.9 % on Friday.

In the case when fewer than 10 % of consumers pick up their parcels from the locker on the first day of delivery, a shortage of available locker spaces is observed on Tuesday, Wednesday, Thursday, and Friday, regardless of the value x_2. On Tuesday, the shortage of available lockers varies from 8.9 % to 10.2 %, while on Wednesday and Thursday, it reaches 60 % at $x_2 = 0$ %.

5. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

As a result of this research, the following conclusions have been made:

1. The issue of last-mile delivery optimization is widely discussed today in both academic and business environments. The increasing volume of deliveries, combined with growing requirements for the delivery process (from consumers, governments, etc.), necessitates the search for alternatives to traditional home delivery. Parcel locker delivery can be an effective solution on the path toward more technological approaches (such as alternative drone launching platforms or autonomous vehicles). A literature review confirms this delivery method's promising development potential.
2. The required capacity of parcel lockers depends on the volume of parcel flow and user behavior (specifically, the time they collect their parcels). This study examines a parcel locker operation model where consumers can pick up their parcels within three days of delivery. As a case study, data from the city of Pardubice (Czech Republic) were used. Taking into account weekly fluctuations in delivery demand, consumer behavior parameters related to parcel pickup speed were identified, under which the existing parcel locker network capacity would be insufficient to meet delivery demand fully. At intermediate stages, limiting the maximum storage time for parcels in lockers may be a more viable solution than physically increasing locker capacity. However, further research and user opinion studies must confirm or refute this assumption. It is important to note that the assessment was conducted under the assumption of constant parcel delivery demand. Any changes in demand (driven by fluctuations in e-commerce volume, population size, etc.) would shift the threshold at which expanding the parcel locker network becomes necessary.
3. Further research could focus on expanding the existing model. For instance, an additional variable could be introduced – representing the number of parcels that could not be delivered due to a lack of available locker space and must be rescheduled for delivery the following day. The results are valuable for forecasting the need to expand the parcel locker network. However, to determine specific districts where expansion is most urgent, the model should be disaggregated, and an assessment of locker occupancy should be conducted separately for each district.

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ОЦІНКА ЕФЕКТИВНОСТІ МЕРЕЖІ ПОШТОМАТІВ: ТЕМАТИЧНЕ ДОСЛІДЖЕННЯ У МІСТІ ПАРДУБІЦЕ ПРИ ЗМІННОМУ ПОПИТІ НА ДОСТАВКУ ПОСИЛОК ТА ТРИВАЛОСТІ ЗБЕРІГАННЯ

Анотація. *Доставка останньої милі є останнім елементом у ланцюзі постачання. Вона відіграє ключову роль у процесах міської логістики, зокрема, пов'язаних із ефективним та екологічним перевезенням товарів у межах міст. Зростання електронної комерції, потреба мінімізації екологічного впливу перевезень та збільшення попиту на ефективну доставку вимагають пошуку варіантів, альтернативних до традиційної доставки додому. Численні дослідження підтверджують, що використання мережі поштоматів допомагає оптимізувати перевезення та знизити логістичні витрати. Цей метод простий у впровадженні, хоча й потребує додаткових інвестицій у поштомати та підтримки від споживачів служб доставок. У цьому дослідженні вивчено роботу мережі поштоматів в умовах, за яких користувачі мають три дні для того, щоб забрати свої посилки після їх доставки, з урахуванням змінного попиту на доставку до поштоматів залежно від дня тижня. Наповненість поштоматів розраховували для різних сценаріїв поведінки користувачів, зокрема для випадків, коли різна частка одержувачів забирали свої посилки на перший або другий день після доставки. Розрахунки виконано на основі даних з Пардубіце, Чеська Республіка (місто з населенням 92362 осіб). Результати показали, що якщо значна частка споживачів відкладає отримання посилки, то пропускна здатність мережі поштоматів може зменшуватися, що призводитиме до затримок у доставці. Ці результати можна використати для вдосконалення управління мережею поштоматів та підвищення ефективності логістики останньої милі. Щоб вирішити проблему недостатньої пропускної здатності, потенційні рішення передбачають обмеження часу зберігання посилок замість негайного розширення мережі поштоматів. Проте необхідні подальші дослідження та відгуки користувачів для підтвердження такого підходу.*

Ключові слова: *доставка останньої милі, поштомат, потік посилок, моделювання*.