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METHOD OF ESTIMATION OF CAR TRIPS INDUCED TO PICK UP PARCELS FROM PARCEL LOCKERS

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Abstract:

For several years, parcel lockers have been rapidly growing in the field of delivery methods as a convenient, time-flexible way of picking up parcels. It reduces the logistics operation in delivery for the individual address by bulk delivering to the locker and individual parcel picking up. Together with saving the mileage of the courier delivery operation, it requires realizing a trip to pick up the parcel. As with every trip, this can be made on foot, by car, or the public transport, depending on the modal split for this particular trip. This article aims to estimate the car traffic induced by trips for picking up the parcel from the locker. It uses the survey data to model customer preferences in parcel delivery, such as desired walking distance, number of parcels picked up, and parcel picking up methods. Then, through the geospatial analysis covering the GZM Metropolis population location and parcel locker location, the number of vehicle kilometres weekly for trips to pick up the parcels is estimated. The research shows a significant difference between urban and rural territories in terms of parcel locker walking accessibility. A significant majority of urban territories' inhabitants are within a walking distance to the locker (according to the desired walking distance researched in the survey), making non-pedestrian trips marginal. However, in the rural areas, a lot of households lie outside of the acceptable walking distance. Finally, vehicle kilometres induced by the parcel delivery were summed up for the area. In spite of being a very small fraction of the total traffic, it still presents an amount of traffic that can be reduced by enhancing parcel locker accessibility.

Keywords: *parcel locker, traffic demand, last mile, parcel pickup*

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1. Introduction

In recent years, parcel lockers have become a key element of urban logistics infrastructure, constituting a crucial element of first- and last-mile deliveries. Offering a convenient and flexible form of parcel picking up, they represent an alternative to traditional home deliveries. Their growing popularity stems from the dynamic growth of e-commerce and changing user preferences. In this context, efforts to increase the efficiency of last-mile deliveries necessitate various analyses of their actual impact on the transport system and the environment.

While parcel lockers are often perceived as an environmentally friendly solution, reducing the number of direct deliveries to customers' doors, a growing body of research indicates the need to account for induced trips – additional trips made by users solely to pick up their parcels. Estimating the number of such car trips is crucial for transport planning, environmental impact assessment, and optimizing parcel locker locations. In particular, this analysis allows us to understand the extent to which parcel lockers actually contribute to road traffic increase and, as a result, target transport-related CO_2 emissions, and to what extent they may generate new burdens on the transport system. Various approaches to estimating the number of induced trips are used in the literature. These include:

- analysis of surveys and declarative data – e.g., research on user preferences regarding the mode of transport used for parcel picking up,
- modelling of transport behaviour – e.g., using GPS data, data from courier apps, or data from ITS systems,
- application of analytical optimization models – e.g., p-median, location-allocation, which take into account population density, accessibility of public transport systems, and other spatial factors,
- detailed environmental analyses – e.g., LCA, which consider emissions associated with the entire delivery and picking up process.

To the authors' knowledge, however, there is no approach to the analysed issue that takes into account the diverse factors influencing the need for trips to parcel lockers, their frequency, and the specificity of trips depending on the age group of users. Therefore, this study attempts to identify and estimate the scale of car trips induced by users using parcel lockers, taking into account the location of parcel lockers and the potential residences of their users. The analyses also took into account the availability of transportation, consumer behaviour, and the age structure of users.

The paper is structured as follows. The first chapter is an introduction to the topic mentioned in this paper. The second chapter presents a literature review on the state of the art connected with the topic. The third chapter treats the methods, data used, and the research area. The fourth chapter shows the results of using the aforementioned methods. Finally, the fifth chapter concludes the work and states that further research is possible in this field.

2. State of the art

The approach to estimating car trips induced to pick up parcels from parcel lockers is primarily driven by the research objective. Therefore, the research areas can be divided into four main thematic groups:

- the influence of parcel lockers on user behaviour and mobility,
- optimization of the location and operation of parcel lockers,
- algorithms and optimization models for cargo distribution, including parcel lockers,
- sustainable development and the environmental impact of parcel lockers.

The following sections of this chapter discuss each research area in detail.

2.1. The influence of parcel lockers on user behaviour and mobility

The development of e-commerce in recent decades has significantly impacted consumer shopping and mobility patterns (Izdebski et al., 2020). With the increasing availability of digital technologies, online shopping has become an integral part of everyday life, prompting researchers to analyse both consumer profiles and the consequences of this phenomenon for transportation behaviour.

A significant number of scientific studies focus on analysing the impact of parcel lockers on transportation choices, shopping mobility, consumer preferences, and user satisfaction. Ranjbari et al. (2023) conducted a pre-test/post-test experiment with a control and experimental group for two residential buildings in Seattle, comparing the system's performance when the buildings were equipped with and without parcel lockers. The difference-in-differences (DiD) method was used to estimate the impact of parcel lockers on delivery vehicle dwell time and courier time spent in the building. The results indicate a significant reduction in courier time spent in the building (50-60%), which may indirectly impact the number of car trips. A 33% reduction in curbside pickup time was also demonstrated, as well as a significant reduction in failed deliveries and parcel thefts.

Hofer et al. (2020) analysed the impact of parcel lockers on customer mobility behaviour concerning picked up and dispatched/returned parcels. The online panel study, conducted among 141 individuals (employees and students) in Graz, Austria, included two questionnaires: sociodemographic data and behaviour related to parcel pickup/return. Activity chains, modal split, and the time and distance of additional trips were also examined. Based on empirical data, it was estimated that 37–42% of parcel pickup/return trips are symmetrical activity chains (e.g., home–parcel locker–home), generating the highest additional traffic. The potential for CO_2 emissions reduction by 27% and a reduction in vehicle kilometres driven for parcel pickup by shifting these trips to more integrated ones (e.g., picking up a parcel on the way home from work) were also determined. The possibility of shifting 12% of car trips to more environmentally friendly modes of transport (walking, cycling, public transport) was also identified with appropriate parcel locker placement. The acceptable distance to a parcel locker was 1.9 km for environmentally friendly transport. Ultimately, in Graz, potential savings amounted to 263,000 km per year, 44 t CO_2, 130 kg NO_x, and 2 kg PM_{10}.

The results of the parcel locker study were also presented in (Bouhouras et al., 2024). Bouhouras et al. conducted a study among students and university staff in Greece and Italy, assessing the level of satisfaction of users of parcel picking up points (PUPs). The survey showed that most respondents were familiar with the PUP service and used it occasionally. The main criteria for selecting a picking up point were proximity to home, lower cost, and time flexibility. Safety and environmental impact were also highlighted. The comparative analysis of the two urban contexts and the analysis of Generation Z preferences regarding urban logistics presented in this publication can contribute to better planning of PUP locations and improved accessibility and communication of courier services.

Also important is the research conducted by Castaño-Herrera et al. (2025) in the Region of Madrid (Spain) as a case study, with more than 1,300 valid observations. The authors used the Generalized Structural Equation Model (GSEM) to analyze e-shopping habits and associated mobility at the individual level, both in actual and counterfactual shopping behavior. They also studied the influence of multiple explanatory variables: sociodemographics, mobility patterns, e-shopping behavior (delivery characteristics and mobility), and psychological and lifestyle preferences. The results show that e-commerce can both reduce and induce additional trips, depending on the location and the consumer's lifestyle.

The dynamic development of e-commerce in recent years has significantly changed the way consumers make purchasing decisions. Contemporary research on consumer behaviour in the online shopping environment indicates the growing importance of factors related to convenience and sustainability. Bucko, Kakalejík, and Ferencová (Bucko et al., 2018) analysed the determinants of online purchasing decisions, paying particular attention to the role of pickup point location and the availability of delivery options. Their results suggest that the proximity and availability of pickup points significantly influence the perceived convenience of shopping, which translates into a greater willingness of consumers to complete the transaction.

The socio-demographic profile of consumers shopping online has been widely analysed in the literature. Studies by Bjerkan et al. (2020), Etminani-Ghasrodashti & Hamidi (2020), and Xi et al. (2020) indicate that age, education level, income, and place of residence have a significant impact on the propensity to use e-commerce. Additionally, individual characteristics factors such as openness to innovation and the level of digital literacy determine the frequency of online shopping (Figliozzi & Unnikrishnan, 2021; Kumar et al., 2023; Zerbini et al., 2022).

The COVID-19 pandemic significantly accelerated the adoption of online shopping, as documented in studies by Cano-Leiva et al. (2024), Diaz-Gutierrez et al. (2024), Kawasaki et al. (2022), and Kumar et al. (2025). Mobility restrictions and health concerns have contributed to the increase in the number of consumers using e-commerce, regardless of previous preferences.

Online shopping influences not only the way goods are purchased but also consumers' travel patterns. Hoogendoorn-Lanser et al. (2019) demonstrated that half of the surveyed consumers did not observe changes in their travel behaviour after implementing online shopping. However, those who used the internet to search for product information were more likely to report changes in their shopping habits, including shortening travel distances for non-grocery purchases.

Ding and Lu (2017) observed that online shopping can increase the frequency of visits to physical stores while simultaneously reducing participation in recreational activities. Xu & Saphores (2024) indicated that online shopping generates additional trips, particularly among consumers with medium shopping frequency living in low-population areas. At the same time, frequent online shoppers adjust other trips to maintain mobility balance.

Spurlock et al. (2020) conducted research in the San Francisco Bay Area, which showed that online shopping deliveries replace approximately 12% of car trips, while the impact on other modes of transportation, such as walking, bicycling, or public transportation, is significantly smaller (approximately 3%).

Ding and Lu (2017) also observed that consumers who shop online are less likely to combine shopping trips with other purposes than those who prefer physical shopping. Other studies (Shah et al., 2021; Shi et al., 2019) indicate that e-commerce influences the choice of shopping destinations, travel routes, and time of day for purchases. Also worth noting is the study by Iannaccone et al. (2021), who compared consumer preferences regarding delivery locations (home delivery vs. pickup points). The results indicate that young consumers are highly prone to using parcel lockers, which may have significant implications for urban logistics planning and delivery infrastructure.

2.2. Optimization of the location and operation of parcel lockers

A key factor influencing the use of parcel lockers is their location. In this area, research typically focuses on spatial analysis, user trajectories, the use of GIS tools, and methods for selecting optimal locker locations. The E-Commerce Freight Study (EMTA (European Metropolitan Transport Authorities)., n.d.) prepared by the Metropolitan Council (March 2024), which examines the impact of e-commerce growth on transportation, emissions, and spatial planning in the Twin Cities region, notes that new facilities located on major roads and near population centers are preferred, micro-hubs and parcel lockers are appearing in densely populated areas, and the convergence of industrial and commercial functions (e.g., stores as distribution centers) is important. The study found that in 2022, 99.3% of VMT and 98.6% of emissions came from personal shopping trips, not deliveries. Scenarios up to 2050 show that fleet electrification, microhubs, and changes in consumer behavior (e.g., order consolidation, shorter routes) could reduce emissions by up to 48%.

Z. Li and Li (2025) proposed a model for optimizing parcel locker locations in a ride-pooling system, using data from taxi trips and candidate locations. The authors propose a p-median model for optimizing parcel locker locations using data from taxi trips in Shenzhen. The model considers the frequency of user location selection and analyzes the impact of passenger demand density on detour lengths. It can be used to estimate the number of car trips to parcel lockers.

Zhang et al. (2025) proposed a model for planning user paths to parcel lockers using GPS-based spatiotemporal trajectory analysis and kernel estimation (KDE), which optimizes the location of parcel lockers and reduces detour distances by up to 68%. The model takes into account parcel characteristics (weight, volume, urgency) and user behavior, which allows for estimating the number of car trips in urban environments.

The growing importance of e-commerce and growing consumer expectations for fast and convenient delivery generate the need for effective last-mile infrastructure planning (Lasota et al., 2024), including the location of parcel lockers (automated parcel lockers, APLs). Advanced modeling approaches that can support decision-making in this area appear in the literature.

Kumar et al. (2025) propose the use of reinforcement learning (RL) and graph convolutional networks (GCN) to optimize the assignment of shipping points in distribution networks. Although their model addresses general resource allocation, its structure can be adapted to the problem of parcel locker location, particularly in the context of dynamic spatial data and changing demand patterns. Wang et al. (2022) present a robust optimization approach to parcel locker location that takes into account demand uncertainty. This model minimizes the risk of unmet demand for variable shipment types, which is particularly important in the context of seasonality and local purchasing fluctuations.

The two-level model proposed in (Yang et al., 2020) integrates transportation objectives (upper level) with the balance of trip generation and traffic assignment (lower level). This approach allows for estimating the number of vehicle trips to parcel lockers, which can support location planning that minimizes the impact on VMT (Vehicle Miles Traveled). An even more complex model was presented by the authors of (Moslem et al., 2024), who proposed a hybrid, distributed, fuzzy, multi-criteria decision-making model for optimizing parcel locker locations in last-mile delivery areas.

Papers (Ensafian et al., 2023; J. Li et al., 2021, 2025) focus on autonomous mobile lockers, analyzing their impact on trip structure and system efficiency. A comparison of operational variants (e.g., courier delivery vs. customer pickup) shows that mobile parcel lockers can significantly reduce the number of user-generated trips, especially in two-echelon systems. Studies (Ensafian et al., 2023; J. Li et al., 2021) indicate that their optimal deployment depends on population density, infrastructure availability, and the possibility of integration with other forms of mobility.

2.3. Algorithms and optimization models for cargo distribution, including parcel lockers

A significant portion of the literature on parcel locker-related cargo distribution systems describes the use of advanced computational methods (e.g., VRP, SA, ALNS, MP-BRKGA-IPR) to plan delivery routes considering different-sized parcel lockers, packing constraints, and disruptions (Wasiak et al., 2017).

Grabenschweiger et al. (2021) describe the vehicle routing problem considering different parcel locker types (VRPHLB). This problem considers both home and locker deliveries, with customers receiving compensation for pickup from the location. The mathematical model considers the packing of parcels into lockers of different sizes. A metaheuristic based on Adaptive Large Neighborhood Search (ALNS) was proposed.

Another variant of the VRPTW problem, VRPPL, which considers three customer types: home pickup, locker pickup, and flexible choice, was proposed by Yu et al. (2022). The authors developed a mathematical model and a simulated annealing (SA) algorithm that demonstrates high performance compared to the Gurobi solver. Experiments were conducted using modified Solomon instances. The model can be applied to delivery planning in systems with picking up points.

The article of Giménez-Palacios et al. (2022) presents an extended VRP model for first-mile logistics, taking into account operational disruptions, changing customer demands, and packaging constraints. This model can be adapted to estimate the number of trips generated by parcel picking up in urban environments, especially in the context of dynamic changes in demand and infrastructure availability.

Konstantakopoulos et al. (2022) classify 16 VRP variants, including those that incorporate picking up points and parcel lockers as elements of the distribution network. Their review of algorithms – from classical heuristics to metaheuristics and hybrid algorithms – provides a basis for selecting appropriate methods for specific spatial and operational conditions.

Kumar et al. (2025) introduce the MDP (Markov Decision Process) approach to assigning shipping points, which can be used to dynamically assign parcel lockers depending on changing demand conditions, resource availability, and operating costs. Integrating MDP with graph convolutional networks (GCN) allows for the spatial structure of the urban network to be taken into account.

In (Buzzega & Novellani, 2023), the authors analyze routing problems in which one or more vehicles deliver directly to customers or parcel lockers. Additionally, they examine the impact of introducing parcel lockers on the routing structure when time windows are taken into account. A set of new mathematical formulations for these problems is proposed, including a branch-and-cut algorithm. Furthermore, the differences between classical routing problems and their variants that incorporate parcel lockers are analyzed, pointing to significant changes in the structure of logistics decisions and the potential environmental benefits of consolidating deliveries.

In turn, Idzikowski et al. (2024) proposed an extension of the classical Vehicle Routing Problem (VRP), with an objective function that minimizes the total travel time. The authors considered a number of constraints, such as vehicle capacity, travel time limits, parking time, and order processing time at parcel lockers. The method was implemented in real-world urban conditions in Wrocław. The developed model allows for estimating the number of car trips to parcel lockers, which is crucial for assessing the impact on VMT (Vehicle Miles Traveled) and GHG (Greenhouse Gas) emissions.

2.4. Sustainable development and the environmental impact of parcel lockers

Sustainable development in urban logistics requires solutions that minimize the negative environmental impact of transport while maintaining operational efficiency. Automated parcel lockers play a crucial role in this context, enabling the consolidation of deliveries and reducing the number of individual courier and shopping trips. Combined with the electrification of the delivery fleet and the development of mobile parcel lockers, parcel lockers are an important element of sustainable urban development strategies, supporting climate goals and improving the efficiency of last-mile distribution systems. Research in this area examines the impact of parcel lockers on CO_2 emissions, energy efficiency, and integration with co-modal systems and renewable energy sources.

Prandtstetter et al. (2021) analyzed the impact of open parcel lockers on CO_2 emissions and distances traveled. They demonstrated that under certain conditions, the machines can reduce total travel distance and emissions by up to 40%, but they emphasized that picking up parcels by users can generate additional vehicle trips. The authors of (Meliaresti & Nahry, 2022) focused on a life-cycle analysis (LCA) of a parcel locker system, which showed that the environmental impact depends not only on deliveries but also on how consumers pick up their parcels. In particular, car trips to the lockers can significantly increase emissions if they are not part of a larger journey (e.g., shopping, commuting).

Research conducted by Peppel and Spinler (2022) shows that optimally locating stationary parcel lockers (SPLs) can reduce CO_2 emissions by up to 2.5% in urban areas, but can increase them by 4.6% in rural areas due to longer recipient journeys. The analyses used an integer linear programming model and a logit model.

Research conducted by Gutenschwager et al. (2023) compared CO_2 emissions for direct deliveries and those using parcel lockers. The results indicate that parcel lockers can significantly reduce emissions as long as recipients do not travel by car.

In his master's thesis at TU Delft, Saggu (2023) assessed the life cycle assessment (LCA) of parcel lockers in the Netherlands. His research estimated, among other things, CO_2 emissions per parcel: 42 g in the city (walking) and 1028 g in rural areas (driving). A study from Oslo by Pinchasik et al. (2025) also shows the potential for CO_2 emission reductions of 13–32% when replacing home deliveries with parcel lockers. The analyses also considered social costs and recipient behavior.

Innovative solutions for parcel lockers are also found in the literature. Kurowski et al. (2023) proposed optimizing the parcel locker network based on user preferences (e.g., a distance of 500 m as acceptable for pickup on foot). According to the authors, a triangular network provides better coverage than a square one. Ghiani et al. (2025) proposed combining parcel lockers with delivery robots as a way to reduce emissions and costs. The proposed model is hybrid in nature with mobile delivery points.

3. Research method

3.1. Assumptions

The main purpose of the research is to estimate the vehicle kilometres driven by inhabitants to pick up a parcel from a parcel locker located in the analysed area. To reach this, it was needed to gather the spatial and behavioural data. Behavioural data was used to develop a probability model of using a car to pick up a parcel. Spatial data were used to estimate the distance to the nearest parcel locker for each inhabitant of the analysed area. Both kinds of data constitute an entry for the model.

3.2. Area description

The analysis was performed for the Górnośląsko-Zagłębiowska Metropolis (GZM), which is one of the largest and most urbanized areas in Poland and Central Europe. This area is located in the southern part of the country within the Silesian Voivodeship as presented in Fig.1. Officially established in 2017, the Metropolis encompasses 41 municipalities, including major urban centers such as Katowice, Gliwice, Sosnowiec, Bytom, Zabrze, Tychy, and Dąbrowa Górnicza. With a total population exceeding 2.2 million inhabitants and an area of approximately 2,500 km², GZM forms a densely populated polycentric urban region characterized by high levels of industrialization, economic diversification, and extensive transport infrastructure.

Historically rooted in the industrial and mining traditions of Upper Silesia and the Dąbrowa Basin, GZM has undergone significant structural transformation over the past decades. Heavy industries such as coal mining and metallurgy have been gradually replaced by advanced manufacturing, logistics, business services, and emerging technology sectors. This economic shift has been accompanied by ongoing efforts to improve environmental sustainability and mobility, positioning GZM as a leading laboratory for post-industrial metropolitan revitalization in Central Europe.

The transport system of the Metropolis is extensive and complex, consisting of a dense road network, regional rail lines, and an expanding system of public transport coordinated by the Metropolitan Transport Authority (ZTM). The area's strategic location at the intersection of trans-European transport corridors (TEN-T) and proximity to the A1 and A4 motorways facilitate intensive freight and passenger flows both domestically and internationally. The Metropolis also hosts Katowice International Airport in Pyrzowice, which serves as a major regional logistics and passenger hub. The integrated spatial and economic structure of GZM, combined with its logistical accessibility and population density, makes it a critical area for research on sustainable urban mobility, freight distribution, and the environmental impacts of transport systems.

3.3. Data

Considering the usefulness of this research, the following data sources were used:
– survey data,
– PESEL database,
– OpenStreetMap data,
– modal split data from the GZM macroscopic model.

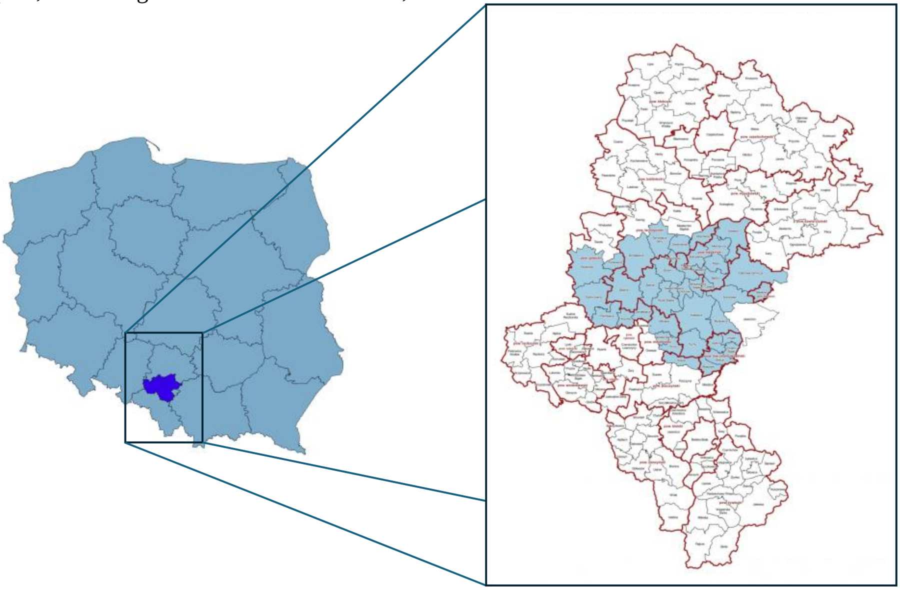


Fig. 1. GZM against the background of Poland and the Silesian Voivodeship. Source: own elaboration based on https://infogzm.metropoliagzm.pl/

The survey data is a part of the complex E-LAAS project survey and collects data about the delivery operation and receiver preferences collected by CATI and CAVI methods throughout the Poland. The receiver preferences part contains information about the desired walking distance to and the usage frequency of the parcel locker. A total of 863 responses in the survey were divided into five age groups, shown in Table 1.

Table 1. The structure of respondents with respect to their age

Age group of respondents	Number of respondents
Below 18	11
18 – 25	88
26 – 35	192
36– 50	378
51 and more	194

The largest share of respondents belonged to the 36–50 age range (378 respondents), followed by the 26–35 and 51+ groups, indicating a predominance of middle-aged participants in the sample. The number of parcels picked up weekly by the respondents, depending on the age group, is presented in Table 2 and Fig. 2.

Table 2. The number of parcels picked up by respondents with respect to their age group

Number of parcels	Age group of respondents				
	Below 18	18– 25	26–35	36–50	51 and more
0	0	1	2	2	1
0,25	1	1	3	9	5
0,5	0	1	5	4	8
1	8	62	118	232	127
2	2	16	48	101	40
3	0	3	13	19	6
4	0	2	3	10	3
5	0	1	0	0	4
6	0	0	0	0	0
7	0	0	0	1	0
8	0	1	0	0	0

As seen in Fig. 2 and tab. 2, most respondents reported receiving approximately one parcel per week, with this category dominating across all age groups. Higher weekly delivery frequencies (two or more parcels) were slightly more common among the 26–50 age range, suggesting a greater intensity of online purchasing activity among middle-aged participants.

It should be noted that not all parcels picked up weekly by respondents are delivered to parcel lockers. Share of the parcels picked up from the parcel lockers is presented in Table 3 and Fig. 3.

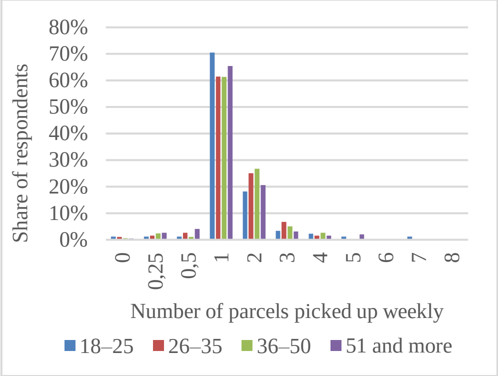


Fig. 2. The structure of the number of parcels picked up weekly with respect to the age group of respondents

Table 3. The share of parcels picked up from parcel lockers with respect to the age group of respondents

Share of the parcels picked up from the locker	Age group of respondents				
	Below 18	18–25	26–35	36–50	51 and more
10%	0	2	7	9	13
20%	0	10	12	38	31
30%	0	0	5	14	12
40%	0	0	8	35	13
50%	1	23	80	121	51
60%	0	4	15	33	26
70%	2	0	1	6	7
80%	1	15	21	44	18
90%	3	3	11	26	9
100%	4	31	32	52	14

Table 3 and Fig. 3 show that in the case of the younger groups, delivery to the parcel locker is a dominant choice. Older respondents prefer a home-delivery method, whereas middle-aged groups mix delivery methods.

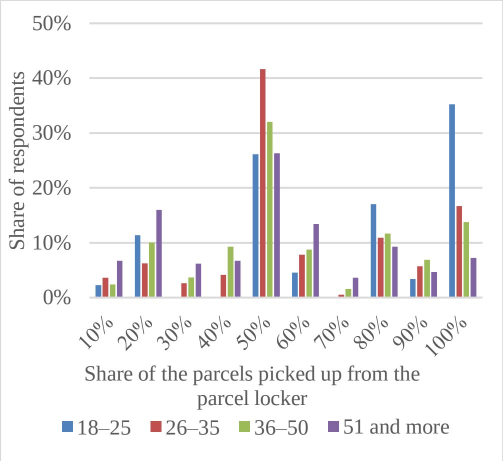


Fig. 3. The structure of parcels picked up from the parcel locker with respect to the age group of respondents

An important piece of information, necessary in the assessment of trips generated by parcel lockers, was whether the parcels were picked up while making other trips, or whether it was during a separate trip motivated only by the parcel locker. The structure of different cases regarding parcel pickup is presented in Table 4 and Fig. 4.

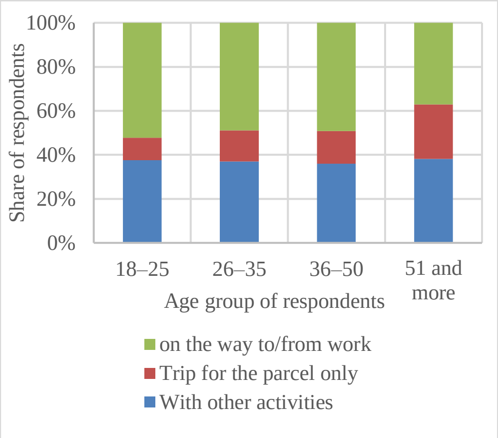


Fig. 4. The structure of the parcel pickup method from a parcel locker with respect to the age group of respondents

Table 4. The structure of parcel pickup method from a parcel locker with respect to the age group of respondents

Parcel pickup method from a parcel locker	Age group of respondents				
	Below 18	18–25	26–35	36–50	51 and more
With other activities	4	33	71	136	74
Trip solely for parcel pickup	0	9	27	56	48
on the way to/from work	7	46	94	186	72

It's worth noting that respondents representing younger age groups more often connect picking up a parcel with other activities. The younger the respondents are, the less often they take a separate trip only to pick up a parcel.
The key data is also acceptable walking distance to the parcel locker, which is presented in Fig. 5.

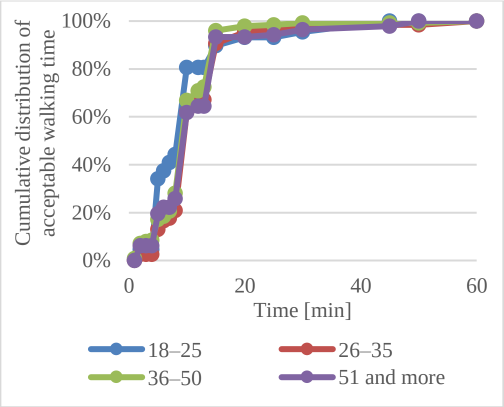


Fig. 5. The cumulative distributions of acceptable walking time for age groups of respondents

Fig. 5 shows that the youngest respondent group is the least likely to travel further distances. This fact can be connected with the fact that younger age groups often combine the trip to the locker with other activities.
The PESEL database, containing the population data of the area of the GZM Metropolis and surroundings, was the second data source used in the research for the purpose of GZM macroscopic model development. Household locations are presented in Fig. 6.

The database covers the following data used in the research:

a) Location: address geocoded to coordinates,
b) Age groups of inhabitants: 0-4, 5-9, 10-14, 15-19, 20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64, 65-69, 70-74, 75+,
c) Number of inhabitants.

OpenStreetMap was the next source of data. Using the QGIS Openstreetmap tool, parcel locker's locations were obtained by downloading the objects labeled: amenity=parcel_locker. Locations of the obtained parcel lockers are presented in Fig. 7.

The last source of data used in the research was the GZM macroscopic model data about the modal split. The values of the share of public and private transport trips are:

– 0,1266 for public transport,
– 0,8734 for private transport.

3.4. Research procedure

The research procedure is presented in the scheme in Fig.8.

The first step of analysis is to properly prepare the data. Using the QGIS software, spatial data from the PESEL and OpenStreetMap databases have been processed. The geoprocessing tool "join attributes by nearest" was used. The output of the processing was adding for each address location from the PESEL database, an attribute of the closest parcel locker, and the straight line distance between those two objects.

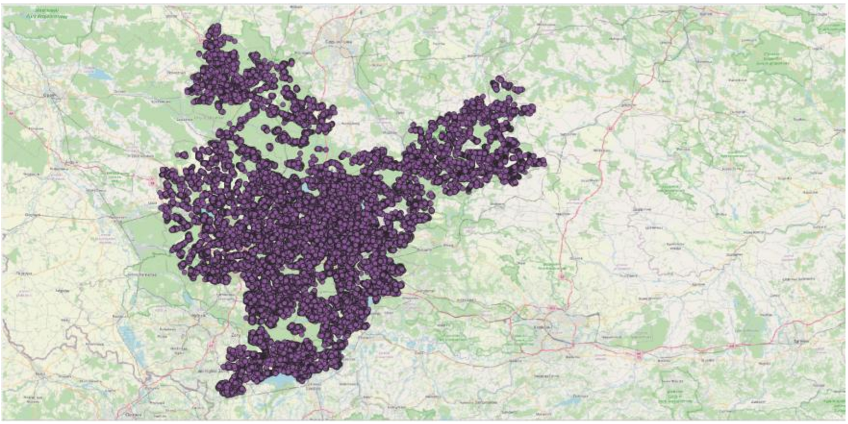


Fig. 6. Locations of households in GZM

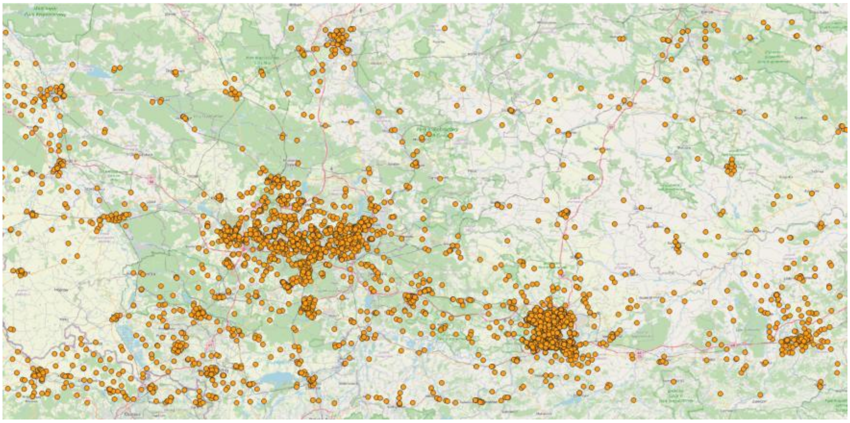


Fig. 7. Locations of the parcel lockers in GZM

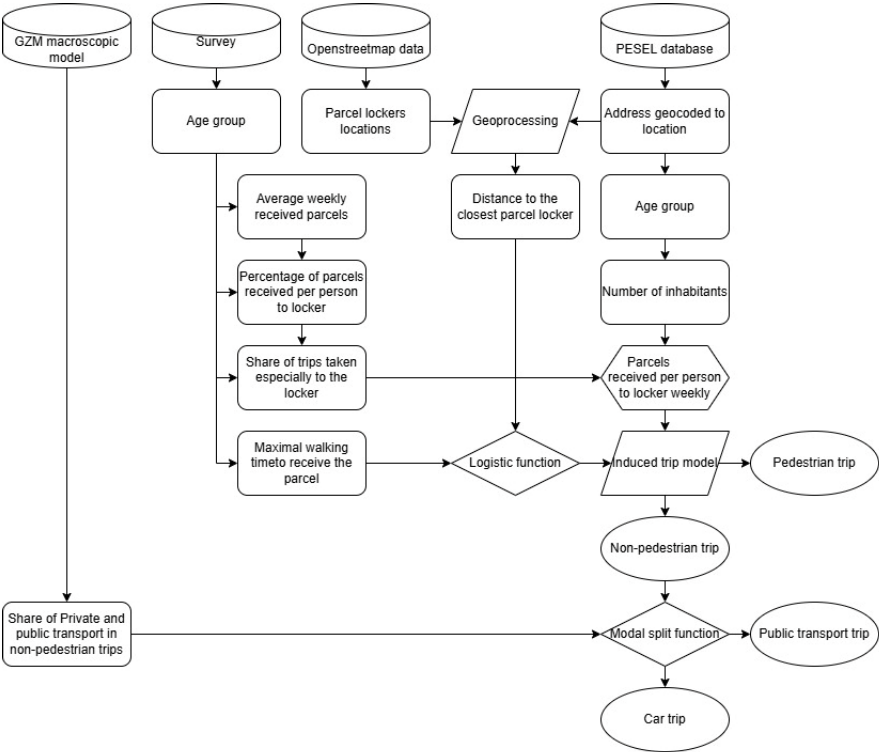


Fig. 8. The scheme of the research method

The induced trip model estimates the number of car trips induced to pick up a parcel from a parcel locker. It combines the following data:

- Users' preferences on the number of parcels picked up weekly, those ordered to the parcel locker, and the share of the parcel picking-up trips that are not a part of other trips. In this research, it is assumed that each parcel is picked up as a separate parcel locker trip. Analysing more than one parcel picking up in each trip will require further research, considering the frequency of this phenomenon, depending on the number of parcels picked up weekly, the time limit of the parcel storage, etc.
- Desired walking time, meaning a probability of taking a motorised trip, is dependent on the distance from the home address to the parcel locker. It is presented as a logistic function and represents an impedance.
- Modal split function and a share of the private and public transport.

The model is presented in formula (1):

$$P(t,ag) = q(ag) \cdot l(ag) \cdot r(ag) \cdot d(t,ag) \cdot m \qquad (1)$$

where:
$P(t,ag)$ - expected number (quantity) of car trips to pick up a parcel within a given walking time t by the inhabitant with the age group ag [trips/week],
$q(ag)$ - expected quantity of parcels picked up by the inhabitant with the age group ag [parcels/week],
$l(ag)$ - expected share of parcels picked up from parcel lockers by the inhabitant with the age group ag [-],
$r(ag)$- expected share of trips taken exclusively to pick up a parcel from the parcel lockers by the inhabitant with the age group ag [-],
$d(t,ag)$ - probability of a motorised trip within a given walking time t by the inhabitant with the age group ag [-],

m- share of the car trips in the modal split of the macroscopic model [-].
Considering the data shown in Section 3.3, the values of coefficients: $q(ag)$, $l(ag)$, and $r(ag)$ have been estimated as average values obtained from the answer from the survey. The values are presented in Table 5.

Table 5. The values of coefficients: $q(ag)$, $l(ag)$, and $r(ag)$ with respect to the age group of respondents

Coefficient	Age group of respondents (ag)			
	18–25	26–35	36–50	51 and more
$q(ag)$ [parcel/week]	1,4176	1,3971	1,4345	1,3518
$l(ag)$ [-]	0,7023	0,6052	0,5868	0,5093
$r(ag)$ [-]	0,1023	0,1406	0,1481	0,2474

Data obtained from respondents on the accepted walking time have been modelled as an impedance function. For the proper representation of the data, the logistic function has been used according to the formula (2):

$$d(t,ag) = \frac{a(ag)}{1 + e^{-b(ag)\cdot(t-c(ag))}} \quad (2)$$

where:
t - accepted walking time
$a(ag)$, $b(ag)$, $c(ag)$ – parameters of the model for each age group ag, where:
$a(ag)$ - upper asymptote (maximum probability),
$b(ag)$ - the steepness of the curve,
$c(ag)$ - the inflection point (midpoint of the curve).
The parameters $a(ag)$, $b(ag)$, and $c(ag)$ were estimated separately for each age group ag using the function "curve_fit" from the SciPy library in Python. This function performs nonlinear least squares optimization to fit the logistic model to the empirical data points.
Fitness of function has been measured by R-squared and MAE (mean absolute error) for each group of respondents. The results are presented in Table 6.
The functions $d(t,ag)$ of probability of a motorised trip within a given walking time t by the inhabitant from the age group ag have been presented in Fig.9. The comparison of the functions $d(t,ag)$ is shown in Fig.10.

Table 6. The parameters of the model: $a(ag)$, $b(ag)$, and $c(ag)$, and measures of fitness for the groups of respondents

Age group of respondents (ag)	Values of the parameters of the model			Values of measures of fitness	
	$a(ag)$	$b(ag)$	$c(ag)$	R-squared	MAE
18–25	0,957	0,458	7,624	0,975	0,502
26–35	0,979	0,432	10,081	0,987	0,032
36–50	0,993	0,419	9,518	0,987	0,298
51+	0,977	0,37	9,861	0,982	0,040

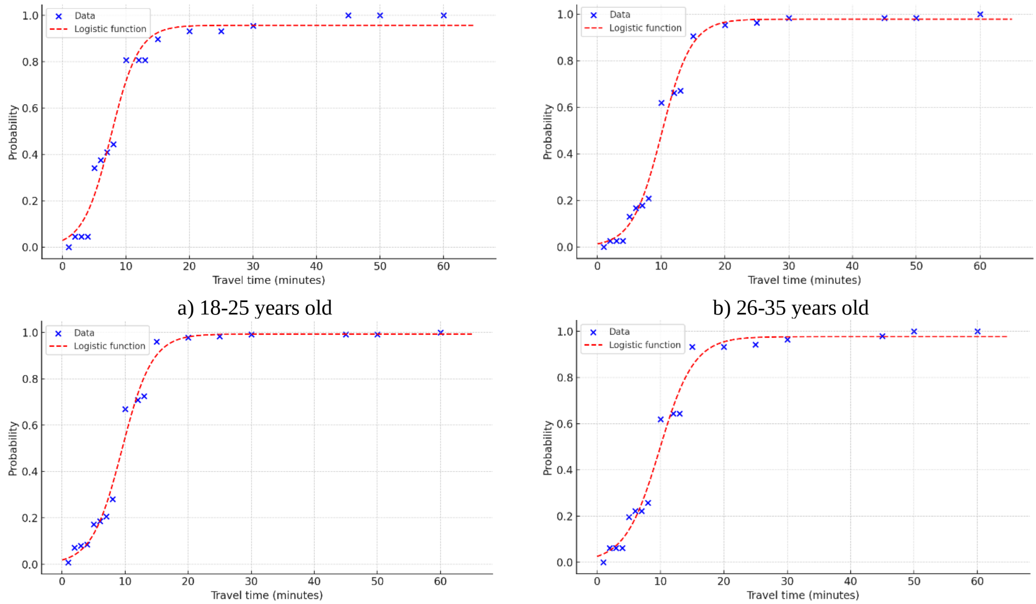
In this research, to assess the share of the public and private transport in the motorised trips, the data from the GZM macroscopic model documentation have been taken. As stated in the documentation, the general share is 0.1266 for public transport and 0.8734 for private transport. Therefore, the value of m has been estimated as 0.8734.
The final form of the induced trip model is a function of the simple user age ag and the accepted walking time t to the parcel locker. Considering the formulas (1) and (2), it can be presented as (3):

$$P(t,ag) = q(ag)\cdot l(ag)\cdot r(ag)\cdot \frac{a(ag)}{1 + e^{-b(ag)\cdot(t-c(ag))}}\cdot m \quad (3)$$

To calculate the amount of vehicle kilometres induced in the area by the inhabitants with the age group ag by driving to pick up a parcel from the parcel locker k within a given walking time t, the following formula (4) has been used:

$$W(t,ag) = 2\cdot\sum_{i=1}^{n_{ag}} P_i(t,ag)\cdot s_i \quad (4)$$

where:
i - a single car ride made by an inhabitant with the age group ag within a given walking time t from the home location to the parcel locker k,
n_{ag} - number of inhabitants with the age group ag,
$s_i(k)$ - distance between the home location of a single inhabitant and its nearest parcel locker,
A trip multiplier of 2 means a round trip to the parcel locker.



a) 18-25 years old
b) 26-35 years old
c) 36-50 years old
d) 51 and more years old

Fig. 9. The models of functions $d(t, ag)$ for each group of respondents

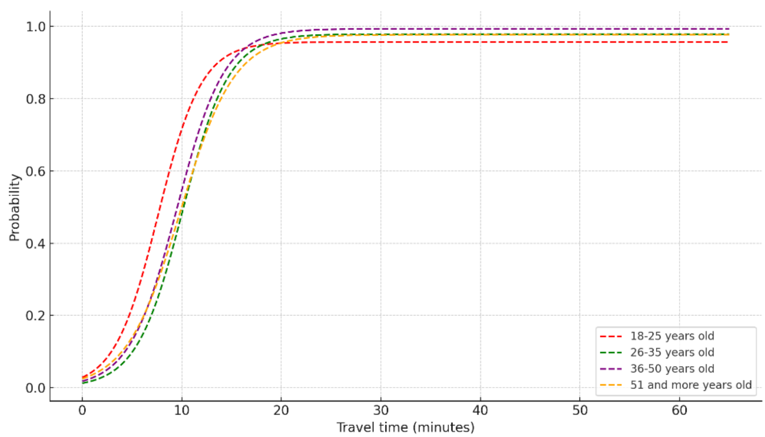


Fig. 10. The comparison of logistic probability functions $d(t, ag)$ for each group of respondents

4. Results

4.1. Spatial data processing

For the selected area, walking times have been calculated for every address. Walking speed was set as 1.2 metres per second. Geoprocessing of the address and parcel locker data gave the information about the distances to the closest one. The data for the counties have been summarized in a tabular way. The walking distance of 12 minutes has been chosen as an average walkable distance to all of the age groups. It can be seen, in the urban counties (those starting from Bytom), that a dominating amount of the population can reach a parcel locker on foot. Walking distances between home and parcel lockers summarised for the counties are presented in Table 7.

Table 7. Home-parcel locker walking distances summarised for the counties

County (Powiat)	Average walking distance (min)	Percent of inhabitants below 12 min walking distance
All	18,07	79,5%
BĘDZIŃSKI	17,61	70,2%
GLIWICKI	35,93	57,1%
LUBLINIECKI	39,74	43,5%
MIKOŁOWSKI	18,39	49,3%
PSZCZYŃSKI	20,86	46,8%
TARNOGÓRSKI	19,24	69,5%
BIERUŃSKO-LĘDZIŃSKI	30,11	22,8%
ZAWIERCIAŃSKI	45,37	40,5%
BYTOM	4,70	97,2%
CHORZÓW	4,75	95,3%
DĄBROWA GÓRNICZA	9,58	91,0%
GLIWICE	7,02	92,7%
JAWORZNO	15,28	72,0%
KATOWICE	4,57	97,0%
MYSŁOWICE	14,18	65,9%
PIEKARY ŚLĄSKIE	6,86	89,9%
RUDA ŚLĄSKA	5,21	96,4%
SIEMIANOWICE ŚLĄSKIE	5,26	97,2%
SOSNOWIEC	6,00	96,1%
ŚWIĘTOCHŁOWICE	4,93	98,0%
TYCHY	9,09	92,3%
ZABRZE	4,97	95,9%

It can be seen in Table 7 that a majority of the cities (starting from Bytom to the bottom of the table) have a parcel locker for the vast majority of inhabitants. In this case, almost none of the trips will be undertaken by car. For the non-urban counties, a greater number of inhabitants have a parcel locker outside walking distance.

4.2. Vehicle kilometres estimation

Using the induced trip model, the amount of vehicle kilometres has been estimated. The results have been presented in Table 8.

Table 8. Amount of the vehicle kilometres estimated by the induced trip model for the picking up of a parcel

According to the walking distance estimation, the results calculated by the induced trip model show precisely that, besides the big population, inhabitants of the urban areas do not have to drive to the parcel lockers in the majority of cases. Driving is needed only in non-urban areas with low population density, scattered housing, and a low number of parcel lockers.

5. Conclusions and further research

5.1. Conclusions

This study contributes to the existing body of literature by addressing the spatial and environmental implications of parcel locker deployment in urban areas, a topic that remains underexplored in previous research. The results demonstrate that the introduction of an extensive parcel locker network significantly enhances accessibility for residents, as almost every location within the analyzed metropolitan area is within walking distance of at least one locker. This widespread coverage supports the transition toward more sustainable last-mile delivery practices by reducing the need for direct home deliveries and associated freight movements in residential zones.

The findings also reveal the number of households outside the urbanized areas located outside walking distance to the parcel locker. This indicates the problem that a substantial number of the trips in these areas will be made by car, leading to additional travel demand. Although the share of such trips in total urban traffic is relatively small,

Table 8. Amount of the vehicle kilometres estimated by the induced trip model for the picking up of a parcel

County (Powiat)	Inhabitants above 18 years old	vehkm weekly	vehkm per person
All	1949436	285248	0,1463
BĘDZIŃSKI	108701	19294	0,1775
GLIWICKI	83459	37417	0,4483
LUBLINIECKI	56264	35168	0,6251
MIKOŁOWSKI	71639	21694	0,3028
PSZCZYŃSKI	80274	22611	0,2817
TARNOGÓRSKI	103408	26064	0,2521
BIERUŃSKO-LĘDZIŃSKI	43423	20437	0,4707
ZAWIERCIAŃSKI	87752	55683	0,6346
BYTOM	110666	1866	0,0169
CHORZÓW	74386	1627	0,0219
DĄBROWA GÓRNICZA	88300	3984	0,0451
GLIWICE	128059	5096	0,0398
JAWORZNO	66647	9198	0,1380
KATOWICE	212974	3897	0,0183
MYSŁOWICE	52958	7480	0,1412
PIEKARY ŚLĄSKIE	39762	1674	0,0421
RUDA ŚLĄSKA	99180	1675	0,0169
SIEMIANOWICE ŚLĄSKIE	47972	702	0,0146
SOSNOWIEC	147942	2777	0,0188
ŚWIĘTOCHŁOWICE	34717	669	0,0193
TYCHY	91968	3617	0,0393
ZABRZE	118985	2618	0,0220

the cumulative distance traveled by these vehicles generates measurable energy consumption and pollutant emissions.
Overall, the results suggest that parcel lockers serve as an effective intermediary between home delivery and centralized pickup, reducing freight vehicle circulation and mitigating congestion in dense urban environments. Nevertheless, to maximize environmental benefits, complementary policies are required—such as optimizing locker placement, integrating them with public transport nodes, and encouraging active or shared modes of access. The study thus provides both empirical evidence and policy-relevant insights into the potential of parcel lockers to contribute to sustainable urban logistics.

5.2. Further research

Future research would broaden the research scope and to precise results presented in this article. First, the integration of advanced geoprocessing techniques based on actual road network distances would allow for more accurate estimation of travel times and spatial accessibility, replacing simplified Euclidean measures. Such improvements would enhance the precision of emission and energy consumption calculations associated with parcel pickup trips.
In addition, forthcoming surveys should employ more consistent age group segmentation to better capture behavioral differences across demographic segments. Distinguishing between respondents from areas of varying urban density would enable identification of the desirable walking distance thresholds specific to compact city centers versus suburban or peripheral zones. Similarly, examining preferred delivery methods across these settlement types could clarify how urban form influences the adoption of sustainable delivery solutions. Also, the modal split for the parcel picking up should be analysed based on the housing density category.
Finally, a comprehensive comparison between the vehicle kilometers, energy consumption, and emissions generated by customer trips to parcel lockers and those saved through optimized logistics operations would provide a holistic assessment of the net environmental effect of this delivery model. Such research would strengthen the empirical foundation for developing data-driven policies supporting sustainable last-mile logistics in metropolitan areas.

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