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SPATIAL ANALYSIS OF THE OOH DELIVERY NETWORK: CASE STUDY OF MEĐIMURJE COUNTY

PROSTORNA ANALIZA MREŽE OOH DOSTAVE: STUDIJA SLUČAJA MEĐIMURSKE ŽUPANIJE

Katarina MOSTARAC
Fakultet prometnih znanosti
Sveučilišta u Zagrebu
Vukelićeva ul. 4, 10000, Zagreb
kmostarac@fpz.unizg.hr

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Petar FELETAR
Fakultet prometnih znanosti Sveučilišta u Zagrebu
Vukelićeva ul. 4, 10000, Zagreb
petar.feletar@fpz.unizg.hr

Nikola ŠIMUNIĆ
Institut za istraživanje migracija
Trg S. Radića 3, 10 000 Zagreb
nikola.simunic@imin.hr

SAŽETAK

Ova studija predstavlja sveobuhvatnu prostornu analizu dostupnosti mreže out-of-home (OOH) dostave u Međimurskoj županiji, Hrvatska, s fokusom na paketomate i mjesta preuzimanja kojima upravlja jedan davatelj poštanskih usluga. Istraživanje se bavi izazovima prostorne jednakosti u logistici zadnje milje u pograničnom području gdje je izražen pad i starenje stanovništva, ruralne i urbane razlike te kontinuirano smanjenje broja stanovnika. Korištenjem geografskih informacijskih sustava (GIS) i multimodalne mrežne analize, studija se fokusira na dostupnost usluge kroz područja obuhvata od 400 m (hodanje), 2.000 m (bicikliranje) i 5.000 m (motorizirana vozila). Metodologija integrira kalkulacije mrežnih udaljenosti s analizom demografske pokrivenosti na osnovu podataka o brojevima kuća za kvantificiranje prostornih nejednakosti u distribuciji usluga. Rezultati pridonose razumijevanju prostorne (ne)jednakosti u suvremenim logističkim mrežama, što je temelj za preporuke za pravedniju logističko planiranje zadnje milje u ruralnim i graničnim regijama.

Ključne riječi: prostorna dostupnost, out-of-home dostava, paketomati, GIS mrežna analiza, logistika zadnje milje

Keywords: spatial accessibility, out-of-home delivery, parcel lockers, GIS network analysis, last-mile logistics.

1. INTRODUCTION

Accessibility and equity in the provision of essential services represents a basis for the sustainable urban development (Van Wee & de Jong, 2023; Geurs & van Wee, 2004). Since digital services and automated delivery systems are widely used, questions of spatial equity extend beyond traditional public services to encompass emerging commercial infrastructures that serve essential daily needs (Campisi

& Di Ruocco, 2025). Differences in accessibility levels question the appropriate spatial scale for calculation and comparison (Van Wee & de Jong, 2023).

Some authors develop indicators such as "location dominance," which accumulates access opportunities with a time-weighted decay function (Wang et al., 2025), while Hansen (1959) described how land use patterns are shaped by the ease of reaching various destinations, establishing a theoretical framework that remains central to contemporary spatial analysis. This framework has evolved to encompass multiple dimensions including transportation systems, land use patterns, and individual characteristics that collectively determine access to opportunities (Geurs & van Wee, 2004). Contemporary accessibility research increasingly recognizes the social dimensions of transport, where limited accessibility can lead to social exclusion and reduced participation in economic and social activities (Preston & Rajé, 2007).

In parallel with public service accessibility studies, the logistics sector has undergone a profound transformation, particularly in the last-mile delivery (Campisi & Di Ruocco, 2025). The logistics industry has increasingly relied on Out-of-Home (OOH) delivery solutions, encompassing parcel lockers (PLs) and Pick-Up/Drop-Off locations (PuL), representing a paradigm shift that redistributes delivery access points across urban and rural landscapes (Last Mile Experts & UPIDO A.G., 2021; Zhang et al., 2025). However, this spatial redistribution introduces new dimensions of accessibility inequality, particularly affecting populations with limited mobility, digital literacy, or proximity to service points (Hofmann-Souki et al., 2024). This shift has been dramatically accelerated by the global rise of e-commerce and subsequent events like the COVID-19 pandemic, which caused explosive growth in B2C parcel volumes, testing delivery capacity and driving consumer preference toward contactless solutions (Kolasińska-Morawska et al., 2022; Sułkowski et al., 2022; Last Mile Experts & UPIDO A.G., 2021).

OOH delivery models are efficient, sustainable alternatives to traditional home delivery (Campisi & Di Ruocco, 2025; Kolasińska-Morawska et al., 2022). The consolidated nature of OOH deliveries leads to notable operational, economic, and environmental benefits, often resulting high delivery rates and reductions in vehicle emissions (DPD Group, 2024; Last Mile Experts & UPIDO A.G., 2021). This contributes to the smart logistics concept, emphasizing technology-based solutions that promote sustainable development, efficiency, and customized customer service (Kolasińska-Morawska et al., 2022; Sułkowski et al., 2022). Recent technological innovations in parcel locker solutions have further enhanced the appeal of OOH delivery through improved user interfaces, real-time tracking capabilities, and integration with mobile applications (Zhang et al., 2025).

Despite the clear benefits to logistics providers (e.g., lower operating costs and increased last-mile capacity), the successful implementation of OOH systems relies fundamentally on ensuring customer acceptance, which involves balancing convenience, cost, and perceived sustainability (Klein & Popp, 2022). However, the rapid development of OOH networks has introduced significant challenges concerning spatial equity, particularly the unequal distribution of services between high-density urban centres and underserved peripheral or rural areas (Campisi & Di Ruocco, 2025; Fried et al., 2024).

Rural areas are faced with challenges including lower population densities, greater distances between service points, and limited transportation infrastructure. Rural e-customers' preferences for delivery methods may differ substantially from urban residents due to spatial exclusion and infrastructure constraints, with socio-demographic characteristics playing a crucial role in determining accessibility to last-mile delivery services (Markowska et al., 2023; Montero-Vega et al., 2025). Studies utilize fine-grained methodologies like address point analysis to quantify these spatial inequalities and identify areas requiring intervention (Zmuda-Trzebiatowski, 2024). Similar methodological approaches have been applied to Amazon parcel locker networks (Schaefer & Figliozzi, 2021).

Spatial accessibility analysis of OOH networks requires sophisticated methodological approaches that integrate network analysis, demographic assessment, and inequality measurement (Schaefer & Figliozzi, 2021; Fried et al., 2024). Geographic Information Systems (GIS) provide essential tools for multi-modal accessibility assessment, enabling researchers to quantify service coverage across different transport modes while identifying spatial inequalities through established indicators such as the Gini coefficient. Contemporary methodological frameworks increasingly incorporate multi-modal perspectives that recognize the diverse transportation options available to different population segments, from walking and cycling to motorized transport (Ni et al., 2024). Such studies underscore the necessity for strategic, data-driven planning to optimize last-mile facility location, ensuring efficiency while promoting equitable access for all residents (Campisi & Di Ruocco, 2025).

This research contributes to the growing body of literature examining spatial equity in last-mile logistics by conducting a comprehensive accessibility analysis of a single postal service provider's OOH delivery network in Međimurje County, Croatia. Međimurje County is Croatia's northernmost region, characterized by unique geographic and demographic challenges and accessibility issues. The county faces sustained population decline over three consecutive censuses (2001, 2011, 2021), aging population, border area depopulation with lower densities in frontier zones, and pronounced rural-urban disparities. Through multi-modal network analysis of 400m (walking), 2000m (cycling), and 5000m (motorized vehicle) service areas, this study quantifies the spatial accessibility and equity of parcel locker and pick-up location services. The research applies established inequality measurement techniques, including the Gini coefficient, to assess service distribution equity and identify underserved populations. The findings contribute to understanding how contemporary logistics innovations interact with spatial inequalities, providing evidence-based recommendations for more equitable last-mile delivery network planning in rural and border regions.

2. MEĐIMURJE COUNTY

2.1 A continuous decline in population

The decline in the population of Međimurje County relates primarily to the last two intercensal periods (2001–2011, 2011–2021), although analyses of earlier demographic periods and sources are important for understanding the current situation. The first official population census of Croatia, and thus of Međimurje, was conducted in 1857, from which time demographic trends have been systematically monitored. For earlier periods, parish registers can be studied to determine the number of inhabitants. It should be borne in mind that parish records are often incomplete and therefore should not be taken with high certainty. According to a parish register from 1802, Međimurje had 42,500 inhabitants and Čakovec 1,369. By the mid-19th century, a rapid increase in population was recorded. According to the first official census, 55,455 inhabitants lived in Međimurje; of these, 2,678 were in the town of Čakovec itself, while interestingly, Prelog simultaneously had 3,049 inhabitants.

When population size is concerned, the period from 1948 to 1991 was marked by strong demographic growth in Čakovec, especially in comparison with the whole of Međimurje. During that period, Čakovec increased its population from 6,947 to 15,999, while Međimurje simultaneously grew from 110,686 to 119,886 inhabitants. Accordingly, the city of Čakovec grew at an average annual rate of 1.83 %, whereas Međimurje grew at only 0.21 % per year. The reason for such growth was the post-war demographic compensation and the migratory inflow of population from surrounding settlements. If Čakovec is compared with other settlements in Međimurje in the same time intervals, it is evident that the central settlement of Međimurje, Čakovec, had the largest increase in population. The index of change in the total population of the settlement of Čakovec amounted to 120.55 in the first observed intercensal period (2001–2011) and 109.03 in the second (2011–2021). Settlements that recorded population growth in the last two intercensal periods, in addition to Čakovec, were: Mihovljan (indices of change – 111.74 and 100.80), Orehovica (indices of change – 100.60 and 108.03), Gornji Kuršanec (indices of change – 105.03 and 100.50) and Pretetinec (indices of change – 101.50 and 101.48). The remaining 73.28 % of Međimurje's settlements recorded overall depopulation in the last two observed intercensal periods, with the most intensive overall depopulation recorded in the settlements of Trnovec (indices of change – 32.80 and 88.72) and Držimurec (indices of change – 41.01 and 94.33).

The last three consecutive censuses confirm a long-term decrease in the total population in most settlements of Međimurje (Map 1). In the first observed period (2001–2011) the population decline is relatively milder and spatially uneven, while in the second period (2011–2021) the decline intensifies and affects a larger number of settlements. This is a structural demographic phenomenon. In the first

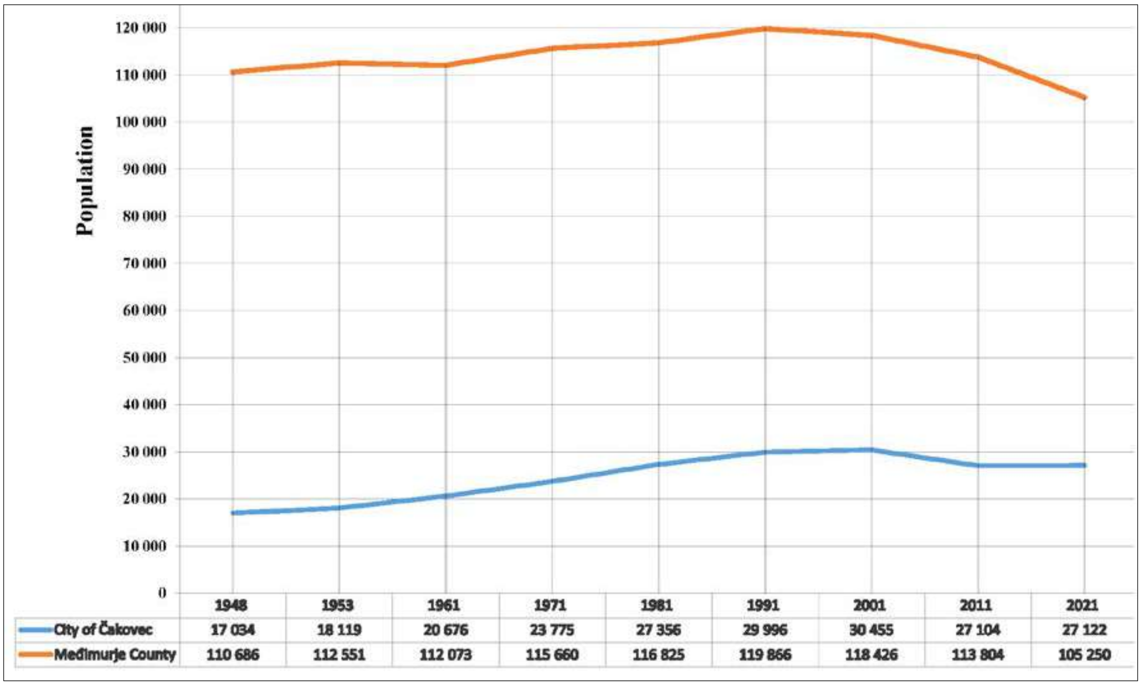
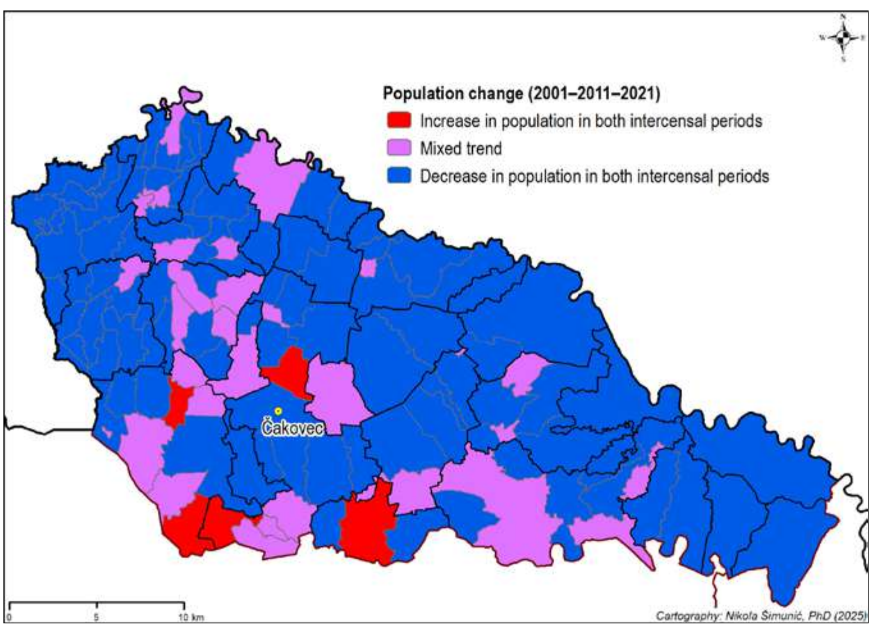
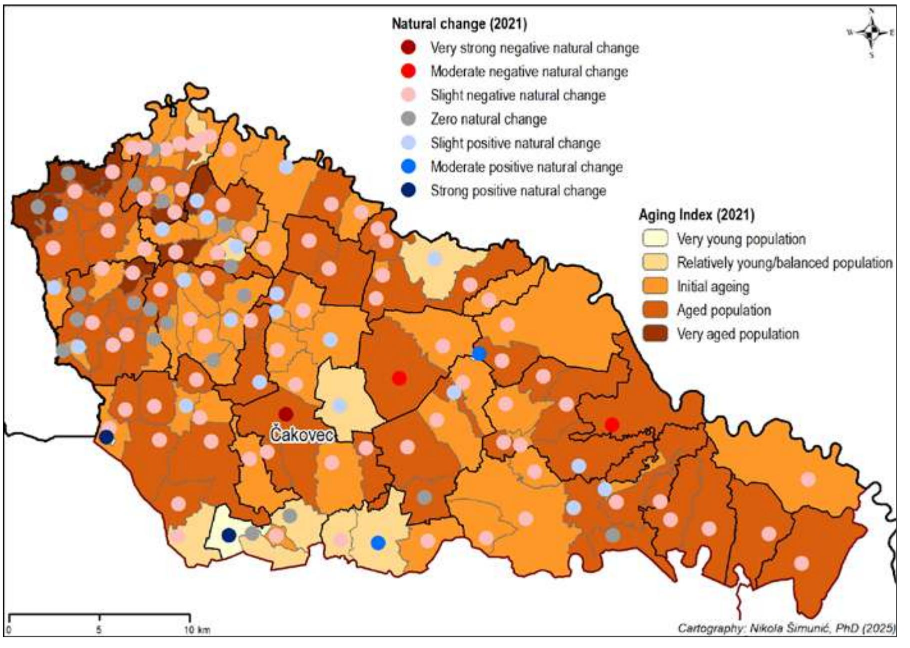


Chart 1. Population trends in Međimurje County and the City of Čakovec by intercensal periods from 1948 to 2021. Source: CBS (DZS) – Population Censuses for selected years.

intercensal period (2001–2011) only three municipalities recorded an increase in population: Pribislavec (index of change in total population 107.07), Šenkovec (index of change 103.94) and Nedelišće (index of change 103.73). The remaining 88.00 % of towns and municipalities recorded overall depopulation of varying intensity: the towns of Prelog (index of change 99.29) and Čakovec (index of change 98.38) experienced a lower intensity of overall depopulation, while the municipalities of Donja Dubrava (index of change 84.43) and Štrigova (index of change 85.87) showed a higher intensity. In the next intercensal period (2011–2021) only the Municipality of Orehovica recorded population growth (index of change in total population 101.30), while the remaining 96.00 % of towns and municipalities recorded overall



Map 1. Continuous population decline during three consecutive censuses (2001, 2011, 2021) in Međimurje. Source: CBS (DZS) – Population Censuses 2001, 2011, 2021; authors' calculations and cartographic processing.



Map 2. An aging population structure in Međimurje County implied by negative natural increase in 2021 (aging index and natural change). Source: CBS (DZS) – 2021 Population Census; authors' calculations and cartographic processing.

depopulation, also of varying intensity: the City of Čakovec (index of change 97.49) and the Municipality of Strahoninec (index of change 96.87) recorded somewhat milder overall depopulation, while the municipalities of Goričan (index of change 83.00) and Vratišinec (index of change 84.32) experienced more intensive depopulation.

Exceptions are associated with the urban center of Čakovec and its suburban ring: there, migration (in-migration from the surroundings) has at times cushioned the natural deficit in the number of inhabitants. However, even in these environments, long-term sustainability depends on a more favorable age structure and the availability of jobs.

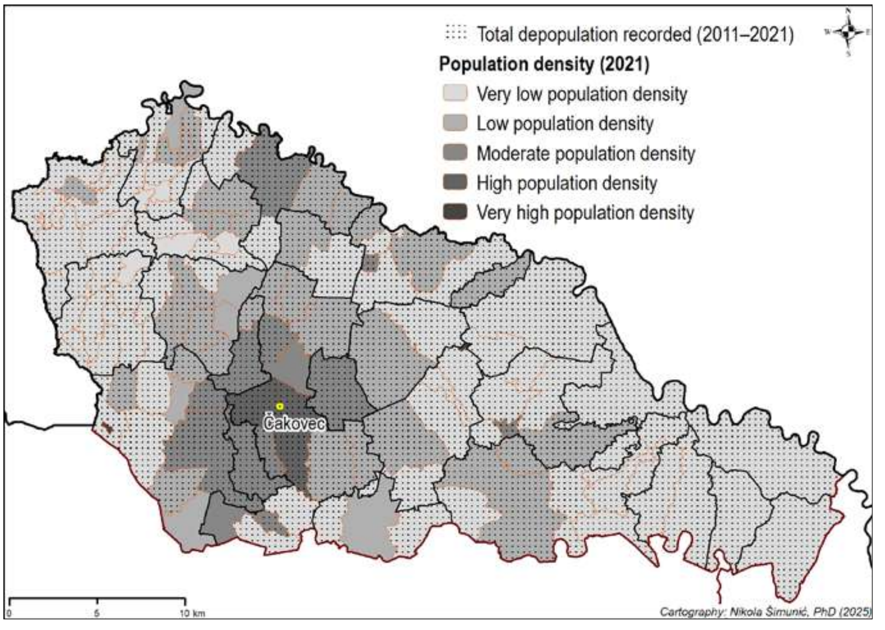
2.2 Population aging and negative natural increase

The age structure in 2021 indicates an elevated aging index in most settlements. A smaller share of the population in the fertile ages results in lower birth rates, while an increased share of older people raises mortality—cumulatively producing a negative natural change. The aging index (2021) was unfavorable in most settlements of Međimurje (89.31 %). The most unfavorable aging-index values were recorded (2021) in the settlements of Praporčan (351.85), Robadje (294.12), Gornji Koncovčak (266.67) and Banfi (264.52). The median value of the aging index was 151.39, which means that for every one young person (aged 0–19) there were 1.5 older persons (aged 60 and over). An equal ratio of young to old was recorded (2021) in the settlements of Čestijanec and Dragoslavec Selo. Nevertheless, a certain portion of Međimurje's settlements (9.16 %) recorded somewhat more favorable aging-index values in 2021, and the "youngest settlements," according to this indicator, were Piškorovec (2.40), Parag (3.96), Kuršanec (23.31) and Orehovica (54.23).

Aging is spatially differentiated: in the centre and suburban rings it progresses more slowly due to the in-migration of younger households, while peripheral and border areas age more rapidly. Consequently, the burden on health-care and social-care systems increases, and the planning of public services (transport, early childhood and education, long-term care) needs to be adapted to local demographic profiles.

2.3 Depopulation of border zones and lower settlement densities

All demo-geographic indicators and the resulting maps clearly highlight border and edge zones as depopulation hotspots. Along these stretches, the following are present simultaneously: lower initial densities, functional peripherality (weaker access to services and labour markets), and long-term emigration. Micro "pockets" of decline also appear in settlements with limited transport accessibility.



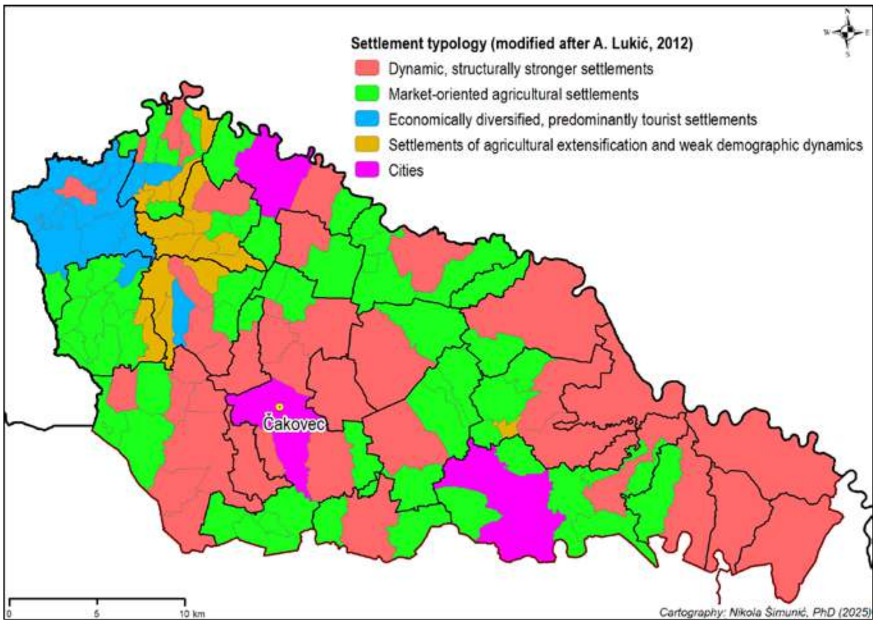
Map 3. Depopulation of border areas of Međimurje County with lower population density in border zones. Source: CBS (DZS) – 2011 and 2021 Population Censuses; authors' calculations and cartographic processing.

2.4 Rural–urban differences

The functional hierarchy of settlements recognizes Čakovec as the leading urban center with pronounced service, educational, and business functions. Suburban settlements benefit from daily mobility/migration and transport accessibility and have relatively more stable demographic outcomes (slower aging, in some places a positive migration balance).

Rural and more peripheral settlements of Međimurje are faced with faster aging, out-migration of the young, weaker generational replacement, and a lower intensity of investment. Settlement typologies adapted to the Croatian context (e.g., Lukić, 2012) show that it is precisely the urbanized and suburban complexes that maintain population stability for longer thanks to access to labour markets and services. In line with Lukić's (2012) typology of urban, urbanized (transitional), and rural settlements, the structure of Međimurje was as follows:

a. Dynamic, structurally stronger settlements: this type included 39 settlements in Međimurje (29.77 %). In settlements of this type, 50,664 persons (48.14 %) lived in 2021, and the total area



Map 4. Differences between rural and urban areas according to A. Lukić's model, modified for 2021. Source: CBS (DZS) – Population Censuses; authors' calculations and cartographic processing after A. Lukić.

amounted to 343.17 km² (47.06 %), from which it follows that the overall population density in 2021 was 147.63 inhabitants/km². The median aging index was 151.63 (2021).

b. Market-oriented agricultural settlements: this type included 60 settlements (45.80 %). In settlements of this type, 26,210 persons (24.90 %) lived in 2021, and the total area amounted to 252.43 km² (34.62 %), yielding an overall density of 103.83 inhabitants/km² in 2021. The median aging index was 148.74 (2021).

c. Economically diversified, predominantly tourist settlements: this type included 12 settlements (9.16 %). In settlements of this type, 2,809 persons (2.67 %) lived in 2021, and the total area amounted to 43.70 km² (5.99 %), yielding an overall density of 64.27 inhabitants/km² in 2021. The median aging index was 223.91 (2021).

d. Settlements of agricultural extensification and weak demographic dynamics: this type included 17 settlements (12.98 %). In these settlements, 3,126 persons (2.97 %) lived in 2021, and the total area was 35.89 km² (4.92 %), yielding an overall density of 87.10 inhabitants/km² in 2021. The median aging index was 149.12 (2021).

e. Towns: this type included 3 settlements in Međimurje (2.29 %). In these, 22,441 persons (21.32 %) lived in 2021, and the total area was 54.05 km² (7.41 %), giving an overall density of 415.22 inhabitants/km² in 2021. The median aging index was 128.78 (2021).

In Međimurje, according to the typology (Lukić, 2012), the following settlement types were not recorded: More accessible, circulation-dependent (commuting) settlements, and Rural periphery settlements.

3. SERVICE PROVIDER NETWORK ANALYSIS

3.1 Out-of-Home (OOH) delivery model

Fig. 1 shows the spatial distribution of a single postal service provider PL and PuL in Međimurje County. PL are primarily concentrated in urban centres, with the highest density in Čakovec. Other than Čakovec, there are also several urban clusters and notable gaps in rural or border regions. Centralized clustering of service points is present around the towns like Prelog, Donja Dubrava, and Donji Kraljevec. On the other hand, the PuL network is more extensive, with substantially greater spatial distribution, especially in smaller towns. Multiple PuL are in proximity to major settlements, particularly Čakovec, suggesting a strong concentration of service provision for residents in urban settings.

The county's unique geographic position as Croatia's northernmost region, bordered by the Mura River (Slovenia) to the north and northwest, and Hungary to the east, creates specific challenges for service accessibility. The OOH network distribution shows uneven distribution alongside international borders with Slovenia and Hungary. The northwestern area along the Mura River shows limited service locations, particularly in the regions around Štrigova and surrounding settlements.

The eastern border areas display higher concentration of service locations, particularly around larger settlements like Mursko Središće and in areas near the main transportation corridors. However, rural villages near the border still show significant gaps in service accessibility.

Fig. 1 also visualizes demographic distribution based on the house number data. This data is crucial in the assessment of the service accessibility to local population. Geographic distribution of the house numbers will help detect areas of the service inaccessibility, providing valuable insight into the network organization and planning. The map reveals substantial coverage gaps in the northwestern and southeastern rural areas. These areas, despite being densely populated, face challenges with accessibility to service provision.

3.2 Buffer zone analysis

The buffer zone analysis of 400 m, 2000 m, and 5000 m is an important factor in evaluating the accessibility of parcel lockers and pick-up locations, reflecting different transport modes used by end users. This step in analysis uses straight-line (Euclidean) distances – a valuable insight for analysis of the spatial distribution of the OOH delivery network. Buffer analysis reveals spatial coverage patterns using three distinct transportation modes: walking (400 m), cycling (2000 m), and car access (5000 m)

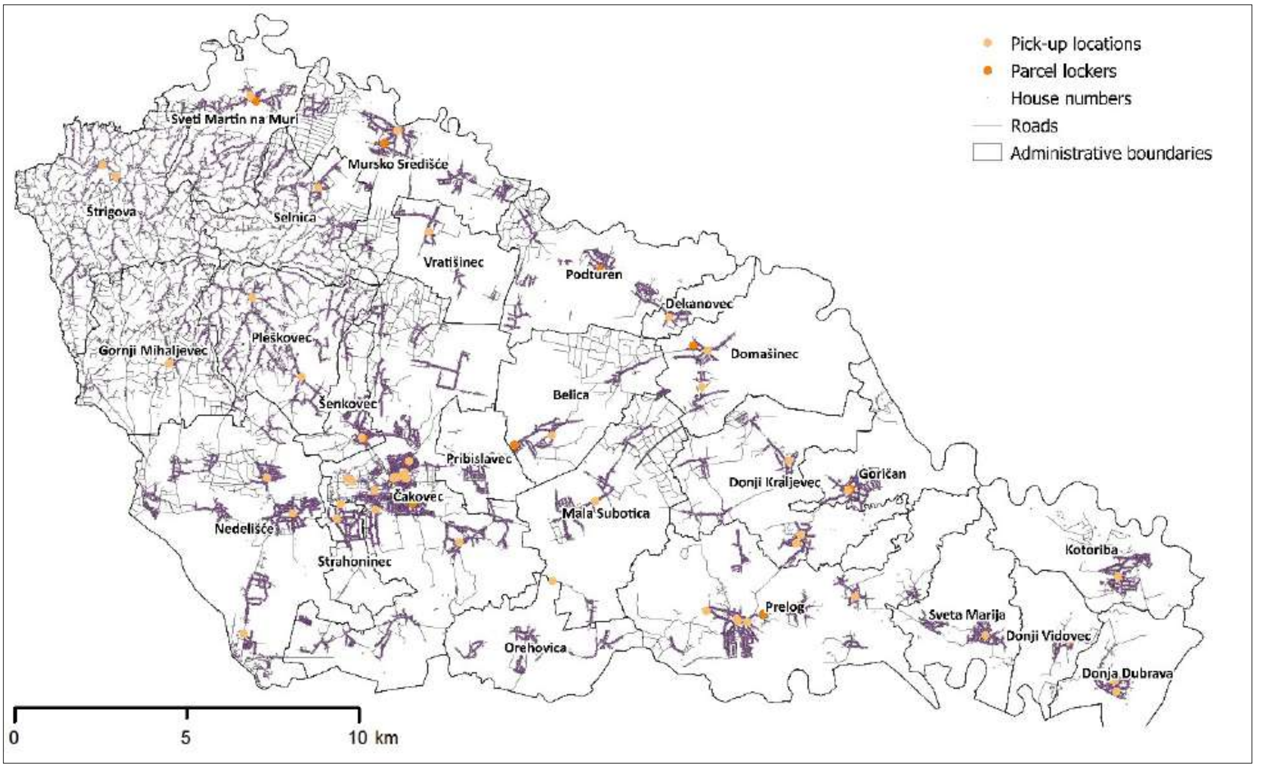


Figure 1. Parcel locker and pick-up locations network
Source: authors' calculations and cartographic processing in GIS.

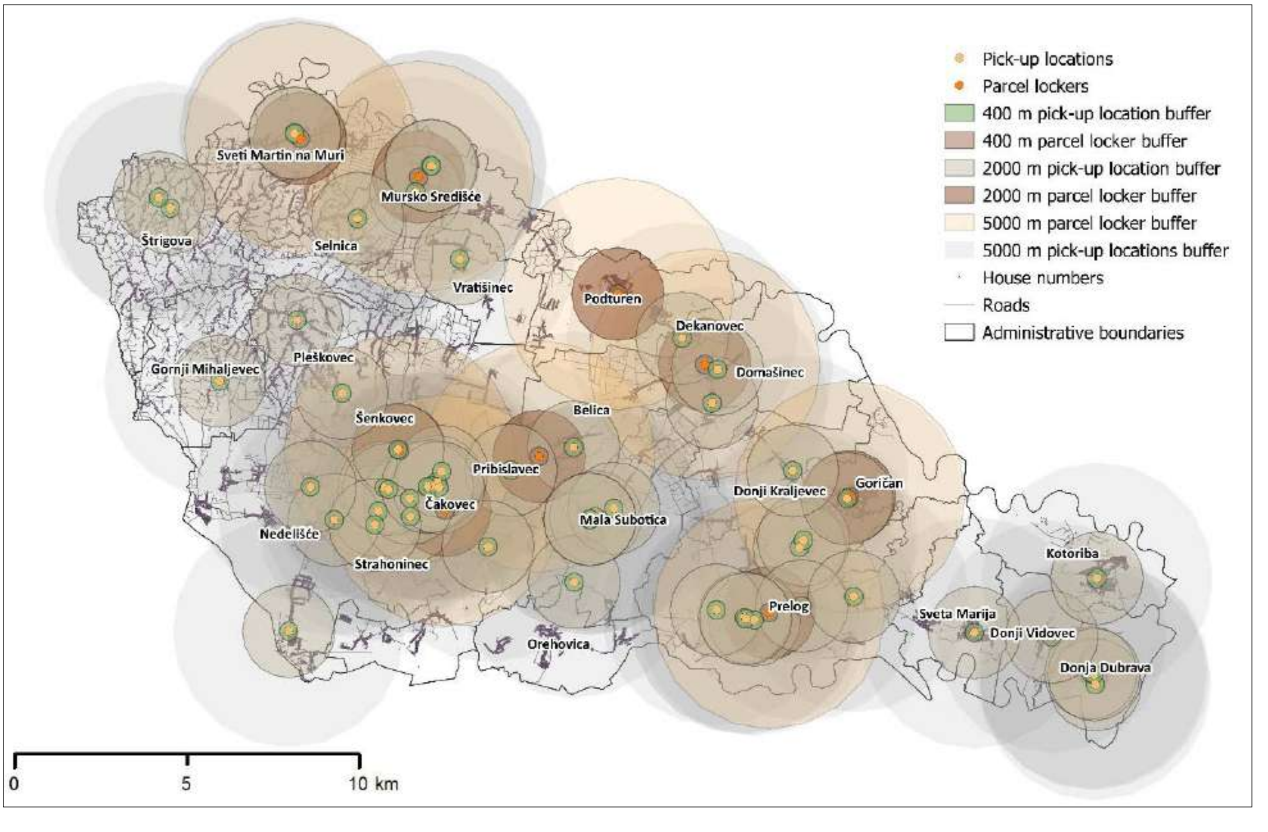


Figure 2. Air distance multi-modal buffer analysis
Source: authors' calculations and cartographic processing in GIS.

buffers. Fig. 2 presents a spatial accessibility analysis of the OOH delivery network in Međimurje County.

Walking Accessibility Zones (400 m)

The 400-meter walking buffer represents the widely accepted walking distance catchment area to essential services, corresponding to approximately a five-minute journey at average walking speeds (El-Geneidy et al., 2014; Somenahalli et al., 2024). This threshold has been consistently validated in public transportation accessibility studies (Chen et al., 2022; van der Waerden et al., 2024). Sarker et al. (2020) confirms that 400–800 m represents the practical upper limit for pedestrian access to public transport stations, establishing this distance as a robust standard for walkable service catchments. The spatial distribution of 400 m OOH network buffer zones reveals that only a small number of addresses (population) have service access within this travel mode. It is evident that service provision to pedestrians is limited to a fraction of population, particularly those living in peripheral and rural areas.

Cycling Accessibility Zones (2,000m)

The 2000-meter buffer represents reasonable cycling distance catchment area. In the urban planning frameworks, particularly the 15-minute city concept, cycling networks within 2km provide effective accessibility to essential services (Wheeldon, 2023). Technical guidelines for bicycle infrastructure design recommend 2km of bike lanes per 1,000 inhabitants as an optimal accessibility standard (GIZ, 2024). This distance threshold is further supported by quantitative analysis of cycling in urban environments, which identifies 2km as an effective cycling catchment for daily mobility needs (Antón-González et al., 2023). The European Cycling Federation's geometric design parameters for cycling infrastructure establish 2km as a standard accessibility threshold for urban cycling networks (European Cycling Federation, 2022). These catchment areas show higher rate of improved territorial and demographic inclusion compared to the prior example. Fig. 2 shows overlapping service areas concentrated around major urban centres including Čakovec, Prelog, and Mursko Središće. However, despite this, significant gaps are still present in rural border areas and peripheral settlements.

Motorized Vehicle Accessibility (5,000 m)

The 5000-meter driving accessibility buffer reflects established practices in European accessibility mapping and service area analysis (Kompil et al., 2019). The OECD's benchmarking framework for accessibility in cities consistently employs 5km as a standard driving accessibility threshold for measuring transport performance and service proximity (OECD, 2019). This threshold is technically validated through GIS service area analysis protocols, where 5km represents an optimal balance between comprehensive coverage and analytical precision (ESRI, 2024). Regional transport accessibility assessments, such as those conducted by Gloucestershire County Council (2020), demonstrate that 5km driving catchments provide effective coverage for accessibility planning while maintaining methodological rigor. At this travel mode, OOH network achieves near-comprehensive territorial coverage across Međimurje County. These extensive overlapping zones demonstrate that all residential areas are within reasonable driving distance of at least one service point. While this threshold successfully eliminates most gaps in service provision, two crucial issues arise. First, substantial redundancies in urban areas are present. Second, this catchment area is strongly correlated with car dependency, which can be challenging for non-drivers and rural population.

This multi-modal approach reflects current best practices in accessibility analysis, where different transport modes serve distinct population segments with varying mobility capabilities (Ni et al., 2024). This methodology aligns with European Commission guidelines for inclusive public transport planning, which emphasize the importance of considering multiple accessibility thresholds to capture the full spectrum of user needs (European Commission, 2024). Recent research by the UPPER Project EU (2024) validates this multi-threshold approach, demonstrating that network-based accessibility analysis using walking, cycling, and driving catchments provides comprehensive insights into service equity and spatial distribution patterns. The integration of these three distance thresholds gives us a perspective of how OOH delivery networks serve different user groups while identifying gaps in service provision.

Several key conclusions with significant implications for equitable last-mile logistics and optimised OOH delivery network can be drawn.

Service accessibility – the pick-up location network provides significantly broader coverage compared to parcel lockers at all buffer sizes, confirming their dominant role in last-mile logistics accessibility within Međimurje County.

Spatial inequality and redundancy – major gaps in service provision are detected in the 400 m buffer zones, where population in peripheral and rural populations has limited service accessibility. On the other hand, 5000 m buffer shows redundant and inefficient service catchment, where most house numbers are included in multiple service areas.

Future planning and network organization – these results emphasize the imperative for strategic network planning, where special attention should be paid to inaccessible service areas. Although this is straight-line distance buffer analysis, it provides valuable foundation for problem analysis and future network planning.

4. NETWORK ANALYSIS OF OOH SERVICE POINTS IN RURAL AREAS

Chapter 3 dealt with air distance accessibility analysis and different buffers for service provision, depending on the selected mode of transport. However, network distance analysis provides more accurate accessibility assessments than straight-line buffers because it accounts for actual road infrastructure and distances. This approach delivers more realistic estimates of service catchment areas considering network connectivity. This is essential for effective logistics planning and equitable service distribution in complex geographic environments like border areas. This chapter presents a network analysis of the proposed three transportation modes.

4.1 Research methodology

This chapter presents research methodology focusing on network-distance-based service area and demographic coverage analysis for parcel lockers and pick-up locations. A multimodal accessibility analysis model of OOH network in Međimurje County will be presented. The research methodology comprises two main steps.

1. Service Area Layer Creation:

For both parcel locker and pick-up location layers, service areas were created for three mobility modes: walking, cycling and motorized vehicle. This was executed using network (road) distances, where catchment areas are identical to those in the previous analysis. Prior to this step, a 100 m buffer for each service area was created to capture the edge zone where accessibility may be transitional or less certain (Figure 3).

The 100-meter buffer zone was applied as a methodological refinement to delineate households situated at the margins of the service areas, specifically enabling analysis of populations with limited accessibility. This auxiliary buffer was systematically generated along the outer boundary of each service area layer to capture the edge zone where accessibility may be transitional or less certain.

The method serves to detect populations that are formally located within the service areas, but who may experience lower convenience than households situated in closer proximity to the service points. Several benefits of this approach can be outlined:

- It quantifies households that are only marginally served, thereby highlighting areas where expansion or infrastructural interventions, such as additional facilities or improved transport connections could most effectively increase accessibility. This approach is valuable in rural and border areas where even small accessibility improvements can impact service quality.
- It offers fine-grained evidence for optimizing last-mile logistics networks while simultaneously balancing equity and efficiency, enabling service providers to intervene based on maximum demographic impact.
- Critically, this delineation makes spatial inequalities visible that are not captured by overall service

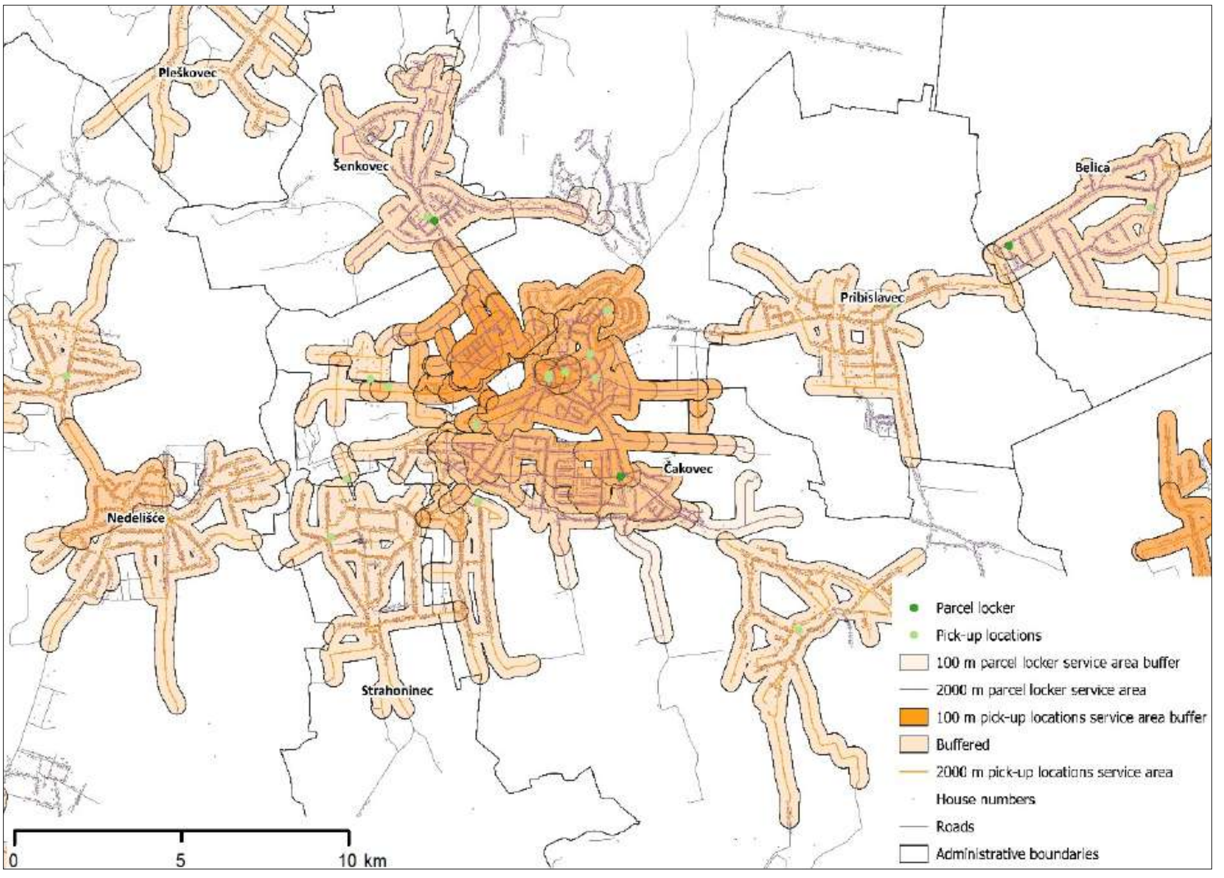


Figure 3. 100 m buffer around service areas
Source: authors' calculations and cartographic processing in GIS.

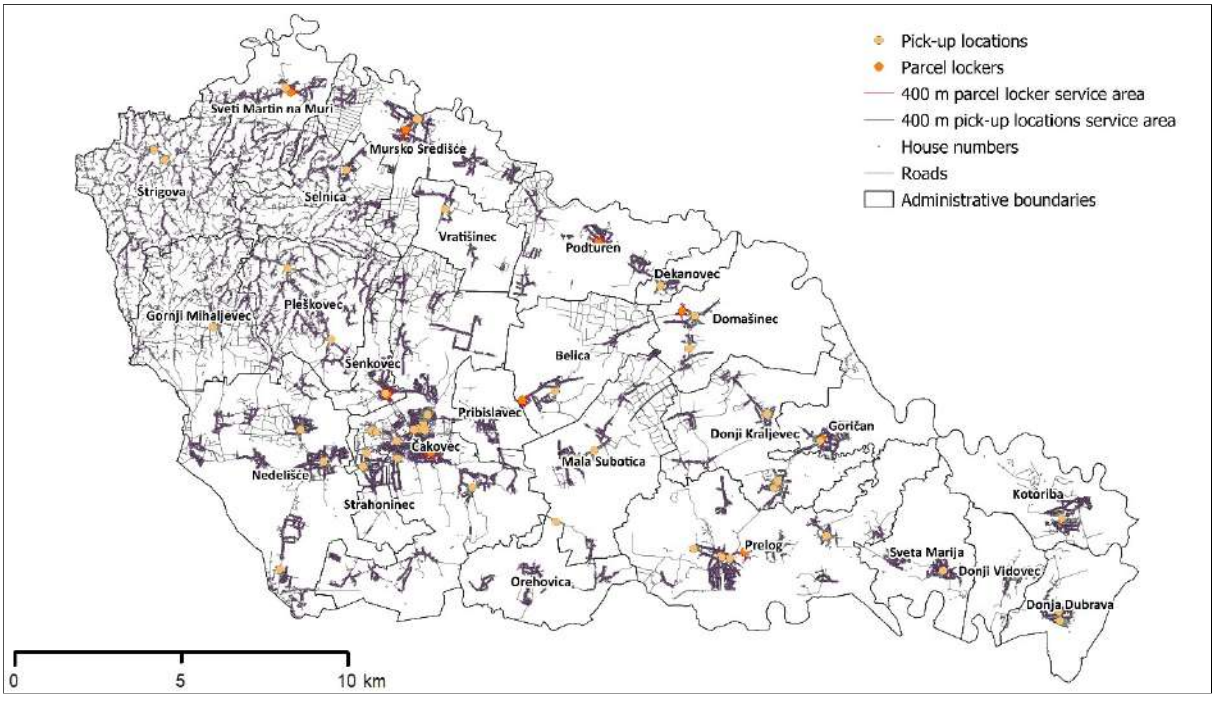


Figure 4. 400 m network distance service area
Source: authors' calculations and cartographic processing in GIS.

2. Household count analysis:

The household count analysis is the second step in the research methodology. This process requires quantifying the total number of households (represented by house numbers) situated within the boundaries of each created network-distance service area. The utilization of house number data is essential for the assessment of service accessibility to the local population and helps to detect areas of service inaccessibility.

This step directly quantifies the correlation between the logistical infrastructure and the actual demographic structure. The aggregated household counts derived from these buffered zones provide a precise assessment of demographic coverage and reveal spatial gaps in the network. Furthermore, executing separate analyses for parcel lockers (PL) and pick-up locations (PuL) refines the results and generates insights for targeted policy recommendations.

This systematic approach offers a methodological framework for optimizing facility location, thereby contributing to improved spatial equity and consumer accessibility to services within the regional logistics system.

4.2 Discussion of the results

4.2.1. Multimodal service area analysis of OOH network

Fig. 4 shows the service catchment area within a 400 meter network distance. As the map shows, accessibility at this catchment area is highly limited and concentrated in dense urban centres, resulting in significant spatial disparities. A very small percentage of households fall within this high-accessibility zone, with pick-up locations covering 7.16 % of households and parcel lockers only 1.39 %. This visualization shows the substantial service gaps for populations in rural and peripheral areas who lack immediate, walkable access to these facilities.

Fig. 5 shows the service catchment area within a 2,000-meter network distance, which corresponds to a reasonable cycling distance for accessing services. This figure demonstrates significantly improved accessibility to services, compared to the 400m walking buffer, with overlapping service areas emerging around major towns like Čakovec, Prelog, and Mursko Središće. According to the analysis, this buffer

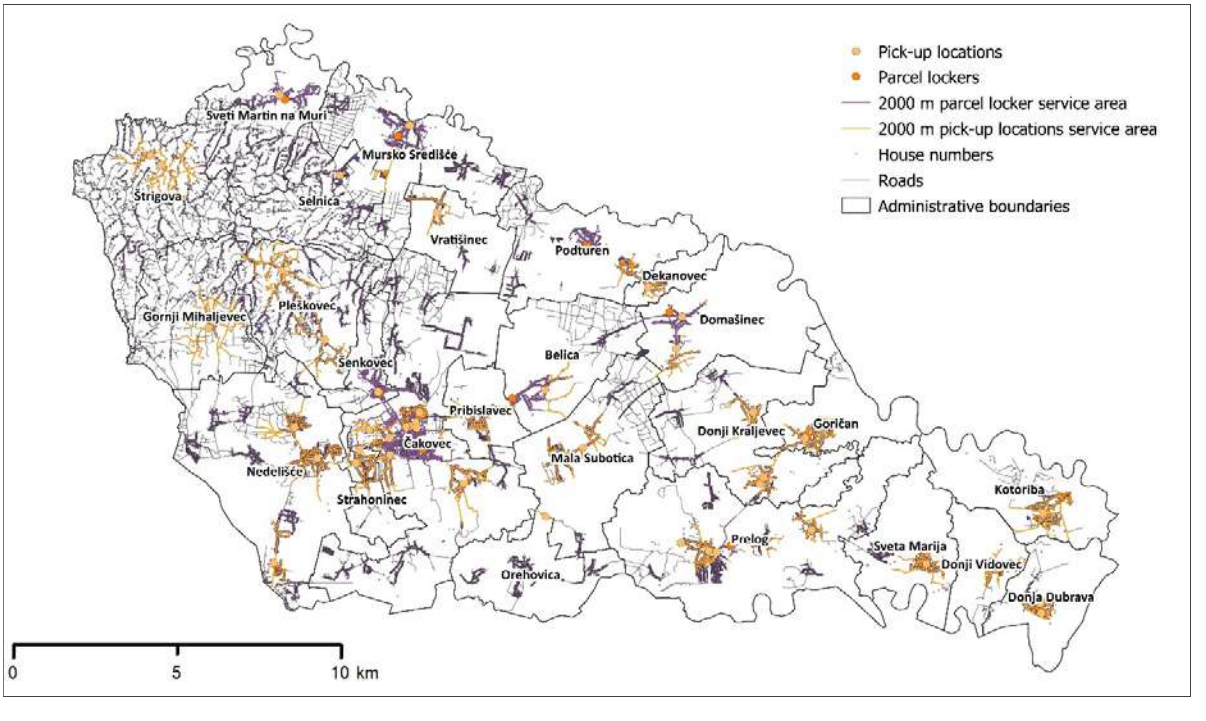


Figure 5. 2000 m network distance service area
Source: authors' calculations and cartographic processing in GIS.

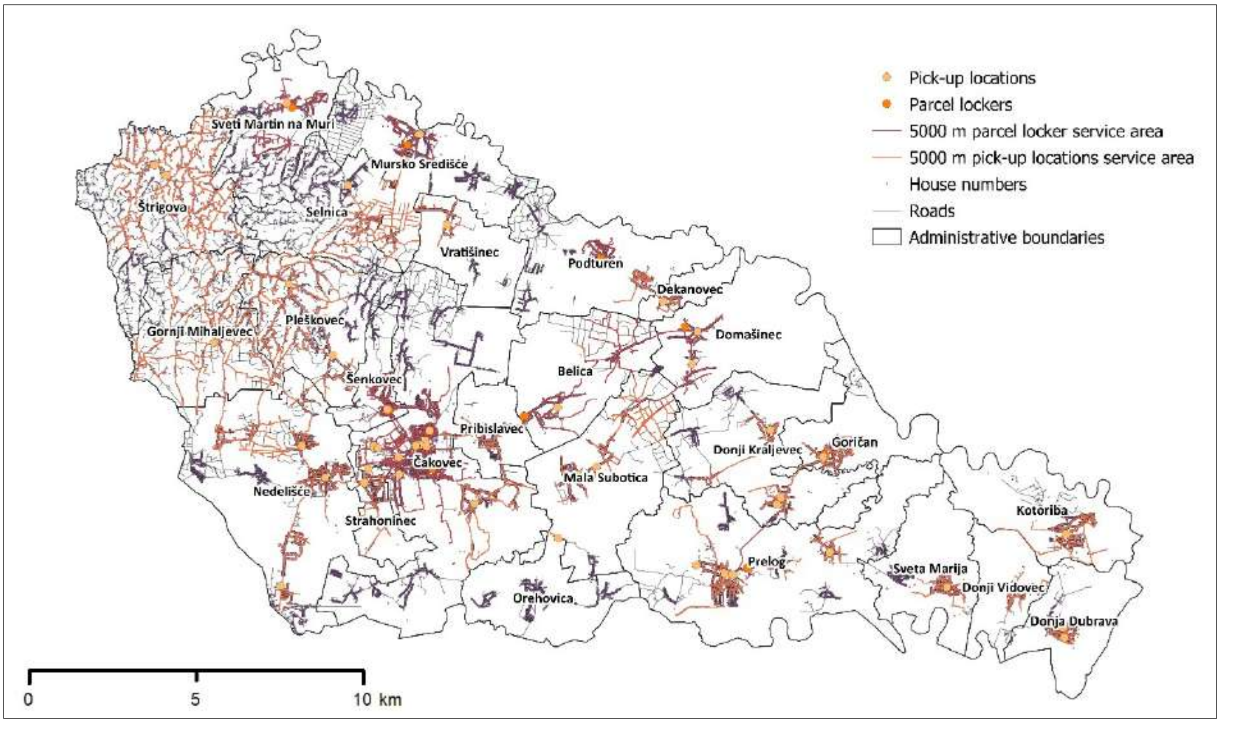


Figure 6. 5000 m service area
Source: authors' calculations and cartographic processing in GIS.

captures 33.47 % of households for pick-up locations and 6.70 % for parcel lockers, showing that pick-up points consistently offer broader coverage. However, the map also reveals that considerable gaps in accessibility exist, particularly in the county's rural border regions and other peripheral settlements.

Fig. 6 shows the service catchment area based on a 5,000-meter network distance, representing accessibility via short-distance motorized vehicle trips. At this range, the OOH network is almost completely accessible across Međimurje County, with extensive overlapping zones ensuring that nearly all residential areas are within a reasonable driving distance of a service point. This service area includes 70.33 % of households for pick-up locations and 13.02 % for parcel lockers. While this broad coverage eliminates most territorial gaps, the visualization also highlights significant service redundancy in urban cores and reinforces the car dependency for rural populations to access parcel services, which can amplify transportation inequities for those without vehicles. The cumulative index for pick-up locations

Table 1. summarizes the accessibility of house numbers to parcel lockers and pick-up locations, depending on the size of the service area.

Table 1. Results of the analysis

	No of house numbers	Catchment (%)	Cumulative index*
400 m parcel locker service area	1,463	1.39	0.014
2000 m parcel locker service area	7,049	6.70	0.081
5000 m parcel locker service area	13,700	13.02	0.211
400 m pick-up location service area	7,541	7.16	0.072
2000 m pick-up location service area	35,229	33.47	0.406
5000 m pick-up location service area	74,019	70.33	1.110

* Cumulative index - the degree of coverage overlap and measures network redundancy

at this distance is 1.11, indicating substantial overlap and suggesting that many households fall within multiple facilities' service areas.

Catchment areas include house numbers ranging from 1.39 % (400 m parcel locker) to 70.33 % (5000 m pick-up location). Mean coverage across all categories is 22.01 %, reflecting moderate overall accessibility. The median coverage of 10.09 % indicates that half of the categories provide relatively low access compared with the 2000 m and 5000 m service areas. The minimum and maximum values confirm strong disparities in spatial reach, while the standard deviation (26.18 %) highlights the high variability in service performance.

The cumulative index measures how coverage expands as the service radius increases. It is useful for detecting saturation points where additional expansion produces diminishing returns. For example, the index of 1.11 at 5,000 m for pick-up locations suggests nearly complete coverage with significant overlap, as many households fall within range of several facilities. This signals a need for careful balance between improving accessibility and avoiding redundant network density. Policymakers and logistics professionals use this for network planning, minimizing operational cost while maximizing coverage efficiency.

The results confirm a strong relationship between service area radius and accessibility. Pick-up locations consistently outperform parcel lockers across all thresholds, reflecting their larger population coverage. However, equity in access remains uneven.

(G) The household count analysis and the subsequent calculation of service coverage across various buffers establish the foundation for evaluating the spatial distribution and accessibility of the OOH network. To precisely quantify this spatial inequality, the Gini coefficient is applied as a standard measure, widely utilized in last-mile logistics and urban accessibility research. This index measures the overall level of equity in service accessibility distribution across the spatial units within Međimurje County. Gini coefficient can be calculated using the following formula (1):

Where:

$$G = \frac{2\sum_{i=1}^{n} i * y_i}{n\sum_{i=1}^{n} y_1} - \frac{n+1}{n} = 0.54$$

G – GINI coefficient
y_i – inverse values of coverage percentages (ascending order)
i – position rank of each sorted value
n – number of observations, ***n=6***

According to formula (1), the GINI coefficient is calculated based on the 6 buffer areas, for the PL and PuL. A low Gini coefficient (close to 0) means most people have similar levels of access to parcel lockers or pick-up points – indicating spatial equity. A high Gini coefficient (close to 1) demonstrates that accessibility is concentrated among only a subset of the population – revealing spatial inequalities and underserved communities.

The application of the Gini index is traditionally used in income analysis, however, its extension to service accessibility quantifies how evenly facilities serve the population. Low values indicate equitable access; high values reveal concentration and inequality. In this study, the Gini coefficient equals 0.54, meaning moderate-to-high inequality in distribution disparities, suggesting a need for more spatially balanced infrastructure, with smaller service areas covering only a marginal portion of the population.

Overall, the analysis provides a methodological basis for optimizing last-mile facility location and contributes to improved efficiency, equity, and consumer convenience in urban logistics planning.

4.3 Study limits and future research

Several key points and limitations to this study should be addressed.

1. Focus on a single service provider. The study provides an in-depth case study but does not capture the complete OOH delivery in Međimurje County. Other postal service providers also have networks that contribute to overall service accessibility. By excluding these competitors, the

study's findings on service gaps and spatial inequality may be overstated, as residents might have access to alternative OOH points not included in this analysis.

2. Static network representation. The analysis presents part of the postal service provider's network at a single point in time. The study does not account for the potential reorganization of the delivery network.
3. Lack of socio-economic and behavioural data: the study effectively uses house numbers to measure demographic distribution and potential demand. However, it does not integrate other critical socio-economic factors, like income levels, car ownership rates, or digital literacy, which significantly influence a resident's ability and willingness to use OOH services.

Future research should focus on dynamic network optimization and the integration of incentive models to understand their impact on customer behaviour and overall system efficiency. Building on the findings of this study, a comparative analysis incorporating the networks of other postal service providers, would provide an in-depth analysis of the OOH service accessibility in the region. Additionally, incorporating socio-economic data could explore the relationship between household income, car ownership, and the choice of OOH services, offering deeper insights into the equity of network design. Finally, investigating the potential for open, interoperable locker networks, could reveal pathways to enhance service density and accessibility in underserved rural and border areas through shared infrastructure models

CONCLUSION

This study provides a comprehensive analysis of the Out-of-Home (OOH) parcel delivery network in Međimurje County evaluating the spatial accessibility and equity of parcel locker (PL) and pick-up location (PuL) services. By employing a multi-modal network analysis with 400 m, 2000 m, and 5000 m service areas, the research reveals significant insights into the state of last-mile logistics in a region characterized by demographic challenges such as population decline, aging, and rural-urban disparities.

The analysis conclusively demonstrates that significant spatial inequalities exist in service accessibility, a finding quantitatively supported by a Gini coefficient of 0.54, which indicates moderate-to-high inequality in service distribution. While OOH models offer benefits in efficiency and sustainability, their implementation in Međimurje County shows a strong urban-centric bias. Pedestrian-level access (400 m buffer) is extremely limited, covering only 1.39 % of households for parcel lockers and 7.16 % for pick-up locations, effectively excluding most rural and peripheral communities. This disparity is particularly pronounced in the county's geographically isolated border regions. While broader accessibility is achieved at cycling (2000 m) and motorized vehicle (5000 m) distances, this reliance on longer travel modes exposes a critical issue: car dependency for rural populations to access essential services. The pick-up location network consistently offers broader coverage than parcel lockers, though the 5000 m buffer reveals significant service redundancy in urban centres, evidenced by a cumulative index of 1.11.

However, the study must consider several limitations. The analysis is limited to a single service provider and thus does not capture the complete OOH delivery market. Furthermore, the study does not account for the dynamic expansion driven by parcel shipment growth. The research also lacks a deeper analysis of socio-economic factors, such as income or car ownership, which could further explain accessibility patterns, as research indicates lockers are often placed in more affluent areas.

These limitations highlight valuable directions for future research. A comparative study incorporating multiple logistics providers would offer a more holistic measure of regional service accessibility. Future research should also investigate dynamic network optimization and the impact of incentive models on customer behaviour. Exploring the potential for open, interoperable locker networks, that already exist in practice, could reveal pathways to enhance service density in underserved areas through shared infrastructure. Ultimately, this study underscores the imperative for strategic, data-driven planning to create a more spatially balanced and equitable last-mile logistics infrastructure, ensuring all residents can benefit from modern delivery solutions. Additionally collected data on socio-economic characteristics (such as car ownership, household income, ICT literacy and other, further data) would significantly contribute to an even deeper analysis of OOH services. The aforementioned variables should be integrated into future studies, which would yield even more precise results.

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SUMMARY

This study presents a comprehensive spatial analysis of Out-of-Home (OOH) delivery network accessibility in Međimurje County, Croatia, focusing on parcel lockers and pick-up locations operated by a single postal service provider. The research addresses spatial equity challenges in last-mile logistics in a border region characterized by population aging, rural-urban disparities, and sustained depopulation. Using Geographic Information Systems (GIS) and multi-modal network analysis, the study evaluates service accessibility through 400 m walking, 2,000 m cycling, and 5,000 m motorized vehicle catchment areas. The methodology integrates network distance calculations with demographic coverage analysis based on house number data to quantify spatial inequalities in service distribution. The findings contribute to understanding spatial equity in contemporary logistics networks and provide evidence-based recommendations for more equitable last-mile delivery planning in rural and border regions.