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MICRO-FULFILLMENT NETWORKS AS AN INFRASTRUCTURAL RESPONSE TO THE CHALLENGES OF QUICK E-COMMERCE IN WARTIME CONDITIONS

Mariia Hryhorak, Olga Karpun, Marharyta Sinaiko. «Micro-fulfillment networks as an infrastructural response to the challenges of quick e-commerce in wartime conditions». *The article theoretically substantiates, for the first time, the feasibility of deploying micro-fulfillment center (MFC) networks as an adaptive logistics infrastructure in emergency situations, particularly martial law. A conceptual model for the formation of an MFC network is proposed, which considers key factors such as spatial demand, the availability and accessibility of resources, as well as potential risks that may arise during crisis situations. The developed model allows for a more efficient distribution of logistics flows and optimization of infrastructure to achieve high operational efficiency under conditions of limited resources.*

Particular attention in the article is paid to the systematization of challenges faced by quick e-commerce in urban environments during wartime, specifically issues related to infrastructure damage, disruptions to transport routes, and the need to ensure uninterrupted delivery of goods in areas where instability is observed *due to the war. It is determined that MFC networks have significant potential in enhancing the resilience of logistics systems, providing quick and efficient access to goods even in challenging conditions.*

An important element of the research is the application of the K-means clustering algorithm to model optimal locations for MFCs in crisis situations, which is a novel approach in the study of urban logistics. Based on the analysis of spatial data and demand, the algorithm allows for the identification of the most advantageous locations for MFCs, ensuring high delivery speed and minimization of logistics costs. This tool enhances the efficiency of logistics systems management, making them more adaptive to the rapidly changing conditions of war or emergency situations.

Keywords*:* quick e-commerce, urban logistics, last mile logistics, fulfillment service, micro-fulfillment centers, micro-fulfillment center network

Марія Григорак, Ольга Карпунь, Маргаріта Сінайко. «Мережі мікрофулфілменту як інфраструктурна відповідь на виклики швидкої е-комерції в умовах війни». *У статті вперше на теоретичному рівні обґрунтовано доцільність розгортання мереж мікрофулфілмент-центрів (МФЦ) як адаптивної логістичної інфраструктури в умовах надзвичайних ситуацій, зокрема воєнного стану. Запропоновано концептуальну модель формування мережі МФЦ, яка враховує ключові фактори, такі як просторовий попит, наявність і доступність ресурсів, а також потенційні ризики, що можуть виникнути під час кризових ситуацій. Розроблена модель дозволяє більш ефективно розподіляти логістичні потоки та оптимізувати інфраструктуру для досягнення високої оперативності в умовах обмежених ресурсів.*

Особливу увагу в статті приділено систематизації викликів, з якими стикається швидка е-комерція в міському середовищі під час війни, зокрема проблемам, пов'язаним з пошкодженнями інфраструктури, порушеннями транспортних маршрутів і необхідністю забезпечення безперебійної доставки товарів у зонах, де в умовах війни спостерігається нестабільність. Визначено, що мережі МФЦ мають значний потенціал у підвищенні стійкості логістичних систем, забезпечуючи швидкий і ефективний доступ до товарів навіть у складних умовах.

Важливим елементом дослідження є застосування алгоритму кластеризації K-means для моделювання оптимальних точок розміщення МФЦ в умовах кризових ситуацій, що є новим підходом у дослідженні міської логістики. Алгоритм дозволяє на основі аналізу просторових даних та попиту визначити найбільш вигідні локації для МФЦ, що забезпечить високу швидкість доставки та мінімізацію логістичних витрат. Цей інструмент підвищує ефективність управління логістичними системами, роблячи їх більш адаптивними до швидко змінюваних умов війни чи надзвичайних ситуацій.

Ключові слова: швидка е-комерція, міська логістика, логістика останньої милі, фулфілмент-сервіс, мікрофулфілмент-центри, мережа мікрофулфілмент-центрів.

Intraduction. The growth in e-commerce has already become one of the most significant trends in the global market, and in the next decade, this sector will continue to develop due to numerous economic, technological, and social factors. Currently, over 33% of the world's population actively shops online, and the volume of the global e-commerce market has already reached $6.8 trillion [1]. According to Promodo's forecasts, by 2027, the e-commerce market volume will exceed $7.9 trillion, which is 39% more compared to today's level. We observe similar trends in Ukraine. According to Similarweb traffic estimates, over 90% of people in Ukraine use the internet, with 78% doing so daily. Therefore, the potential for online business growth is significant. In Ukraine, this figure is three times lower than in the USA and

Britain: approximately 15-20% compared to 45-50% in certain segments [2].

E-commerce has a powerful impact on the development of logistics, transforming traditional logistics models and posing new requirements for the organization of transportation, storage, and delivery processes. One of the key challenges facing logistics in the context of the rapid development of e-commerce is the need to handle a large number of small orders that require prompt picking, personalized packaging, and fast delivery to the end consumer. This fundamentally changes the nature of logistics operations, which were previously focused mainly on large batches of goods and centralized deliveries. Currently, the role of last mile delivery is growing, becoming critical in terms of both meeting customer expectations and the overall cost of logistics services. In the context of e-commerce, the requirements for warehouses and distribution centers are also changing. Modern logistics centers are transforming into high-tech facilities equipped with automated storage, sorting, and real-time tracking systems. Warehouse location is acquiring a new logic – more and more companies are creating decentralized networks of micro-fulfillment centers near major consumer markets to shorten delivery times. As numerous studies of customer expectations show, delivery speed is one of the main reasons for abandoning purchases. Therefore, the instant delivery segment, where consumers can receive their order within 15-30 minutes, is one of the fastest-growing. This indicates the need for the development of logistics infrastructure in urban environments, in particular, last mile delivery fulfillment centers, as well as the need to search for new business models for supply chains in the context of quick e-commerce.

Wartime conditions cause significant transformations in the economic, social, and infrastructural environment, which fundamentally affects logistics and consumption patterns. In this context, quick e-commerce (Q-commerce) acquires particular importance, as it can promptly provide the population with essential goods under conditions of limited access to traditional retail channels. It reduces risks for citizens by minimizing the need for physical movement and simultaneously supports the economic activity of small and medium-sized businesses through digital sales channels. Q-commerce also contributes to increasing logistics resilience: thanks to digitalization, flexibility, and the ability to scale quickly, it promptly responds to changes in the geography of demand, particularly due to population displacement or changes in supply conditions [3]. In wartime, this model stimulates the development of new logistics solutions, including micro-fulfillment centers, which allow for reducing the distance to the consumer and ensuring fast order fulfillment. Thus, quick e-commerce becomes not only an adaptive form of retail but also a tool for ensuring social stability, economic resilience, and the development of innovative logistics infrastructure.

Literature and researches review. The problematics of last mile logistics in urbanized environments have gained widespread scientific and practical interest in the context of the rapid growth of e-commerce, the increasing number of deliveries, and the burden on urban infrastructure. Foreign researchers indicate that traditional logistics approaches prove ineffective in conditions of limited space, high population density, traffic congestion, and environmental challenges characteristic of modern cities.

Among recent publications, some ideas and provisions that form the theoretical basis and justification for the relevance of the topic were used for our research. In particular, the works of contemporary authors thoroughly investigate the problems of last mile logistics in the context of the growth of e-commerce and urbanization. Special attention is paid to the implementation of sustainable solutions, such as micro-fulfillment centers, mobile pick-up points, the use of electric vehicles and cargo bicycles, as well as the application of digital technologies to optimize routes and delivery processes.

The authors [4] drew attention to the need to study the mobility of goods in the urban environment and to develop decision support tools considering social, economic, and environmental indicators in the appropriate spatial-temporal scale using modeling methods. They substantiated that urban mobility encompasses not only commercial activities in the central areas of the city but also the transportation of people and goods in a broader context. The participation of all actors in the production and logistics chains – both public and private sectors – is critical for optimizing transport commercial activities within urban areas. Urban logistics studies the mobility of goods and services in cities to achieve an optimal balance between time, distance, and costs. These two concepts – urban mobility and urban logistics – are closely related and cannot exist without each other. Urban logistics is always an integral part of the urban mobility system. Consequently, a strategic approach to the development of urban logistics should consider the type of city, its economic and social ambitions, the professional structure of the population, demographic characteristics, and other factors that contribute to or determine the evolution of the urban environment [5].

The work [6] presents a thorough bibliometric analysis of scientific literature dedicated to urban last mile logistics in the context of omnichannel retail. This analysis showed that the largest number of publications falls on the period after 2020, which is associated with the rapid growth of e-commerce due to the COVID-19 pandemic [7] and others. The work [8] explores the connection between last mile logistics and the concept of smart cities, emphasizing the positive role of digital technologies in solving last mile problems. One of the key areas is the implementation of green technologies, including the use of electric and hybrid vehicles for delivery, which contributes to reducing CO2 emissions and improving air quality in cities. In addition, the thematic structure of research demonstrates that the concept of "sustainable development" occupies a central place in scientific discussions, but requires further development in the context of e-commerce logistics. In particular, the issues of reducing the ecological footprint, increasing energy efficiency, and implementing sustainable transport solutions remain open.

A new official publication by the World Economic Forum, prepared in collaboration with Accenture, emphasizes that the increase in traffic congestion, greenhouse gas emissions, and negative impacts on public health are among the key hidden costs associated with the intensive development of urban delivery [9]. This once again underscores the relevance of rethinking urban last mile logistics models, taking into account social and environmental consequences.

Additionally, a systematic literature review conducted in the study «Sustainable Urban Last-Mile Logistics: A Systematic Literature Review» (2023) covers 102 scientific works for the period 2016–2022 [10]. It emphasizes that the last mile is the most costly and inefficient part of the logistics chain, causing significant economic, environmental, and social external effects. The study also indicates the need to develop new urban logistics models that would take into account the principles of sustainable development and contribute to reducing the negative impact on the environment. Another study, "Sustainable and Efficient Last-Mile Delivery in Cities," prepared by the World Economic Forum in collaboration with Accenture, predicts that without intervention, emissions from deliveries in urban centers could increase by 60% by 2030 [11]. The report highlights the need to implement sustainable and innovative practices in the field of delivery, such as the electrification of vehicles, route optimization, and the use of alternative modes of transport, to improve the quality of life and support a thriving business environment.

Last mile logistics, as a component of urban logistics, focuses on the delivery of goods directly to the end consumer, which has led to a rapid increase in the number of shipments within urban areas. Today, a large number of companies deliver parcels, food, clothing, and other everyday goods in cities. Each of them faces a number of challenges due to the specifics of their operating model: whether the company specializes in certain categories of goods, whether it uses its own logistics infrastructure, whether it has its own fleet and driver personnel, etc. All these companies are simultaneously participants and factors in the problematics of last mile logistics in the urban environment – they not only ensure the execution of delivery but also experience the impact of its complexities and limitations [12].

Many researchers emphasize that the development of e-commerce exacerbates existing urban problems, particularly the growth of traffic congestion and emission levels. This requires not only managerial decisions but also technological innovations, including the implementation of urban logistics centers, micro-platforms, electric vehicles, and cargo bicycles for delivery in pedestrian and quiet zones.

One of the promising solutions is the creation of micro-hubs, which allow for the consolidation of deliveries within a specific district or street network, instead of several retail operators sending separate vehicles to the same location. Such logistics points become key nodes supported by digital tracking technologies and shared logistics tools. The integration of micro-hubs, digital platforms, and collaborative logistics models is a driving force in the transformation of urban delivery. Thanks to these approaches, cities can not only reduce traffic congestion and pollution levels but also reclaim urban space for residents, making it safer, more comfortable, and more livable.

Micro-fulfillment centers can be considered a new stage in the development of goods distribution in urban areas, which also includes storage solutions. According to [13], MFCs are small fulfillment centers located in the city center or business activity centers, functioning as forward operating bases for quick, usually online, services. Their role is extremely important for last mile logistics, as they bring the resolution point of the supply chain closer to the end consumer. They can be considered small distribution warehouses, strategically located in cities for order fulfillment, occupying much less space than traditional large retailer warehouses [14]. The authors [15] note that MFCs actively use automated or robotic movement of goods with a simultaneous combination of manual labor. They can combine traditional technologies and automation with in-store picking, while their main goal is to bring goods closer to the end consumer, which significantly increases the speed of delivery or pickup [16]. Some researchers believe that MFCs are a mobile order fulfillment system that can radically and very effectively use mobile technologies and real-time delivery solutions [17]. Thus, MFCs have 2 main components: software management systems that process online orders, and physical infrastructure, including robots that pick items from warehouse aisles and deliver them to packers or directly to the customer.

The work [18] demonstrated that the use of MFCs can become a catalyst in solving the problem of sustainable urban last mile logistics, which will contribute to reducing CO_2 emissions in urban areas. This concept can help alleviate congestion in urban areas, as fewer vehicles will be needed for the delivery of goods due to the reduced distance to the consumer through the placement of MFCs in city centers and other strategic urbanized locations characterized by proximity to the end-user [19]. As a result, customers/city residents will receive a number of benefits: faster delivery, lower noise levels due to reduced congestion, fewer road accidents, and cleaner air due to reduced CO_2 emissions, which may even increase their life expectancy [20]. In addition, automation and the use of new technologies in micro-fulfillment centers will help reduce order fulfillment times, which will increase customer satisfaction and delivery efficiency. These results can be used to significantly reduce the problem of urban last mile logistics, emphasizing the importance of using micro-fulfillment centers – a solution that combines storage, consolidation, and delivery of goods to the end consumer in an efficient and perfect manner with minimal environmental impact.

It should be noted that in Ukrainian-language scientific literature, the problems of the last mile in the urban logistics system have been studied fragmentarily, that is, by individual partial indicators, and their results are presented mainly in the materials of scientific and practical conferences. Among the scientific publications whose ideas are used in this article, it is worth noting the article by Ilchenko N.B. and Kotova M.V., which summarizes a set of factors influencing decision-making regarding the organization of goods delivery in the e-commerce system [21]. Datsenko D.R. and Kunytska O.M. drew attention to the placement of logistics infrastructure facilities in cities and proposed an approach to determining the location of an urban distribution center based on the logistics stability index [22]. Oliynyk O. investigated the synergy of e-commerce and fast commerce in the food industry [23]. Sumets O. and Klymovych R. investigated the integrative effect of combining fulfillment and logistics in serving customers in the online trading system [24]. The problem of forming and developing freight flow consolidation centers in the urban environment is most fully and thoroughly researched in the works of Savchenko L.V. [25, 26, 27].

Thus, the analysis of literary sources indicates a multifaceted approach to the study of last mile logistics problems. The research covers various aspects, including the sustainable development of the urban environment, the reduction of greenhouse gas emissions, the alleviation of congestion, the improvement of the quality of life of residents, as well as the operational efficiency of delivery and the application of innovative logistics solutions – such as micro-hubs, automated pick-up points, cargo bicycles, and electric vehicles. Significant attention is paid to the implementation of digital technologies for tracking deliveries and coordinating participants in the logistics process.

However, it should be recognized that a separate important component of this topic – the formation and development of micro-fulfillment center (MFC) networks as a key last mile infrastructure – still remains insufficiently studied. MFCs play a strategic role in ensuring quick and efficient delivery in the context of the rapid growth of online trading, especially in the segment of quick (on-demand) e-commerce. Their functional significance is enhanced in the context of the need for diversified warehousing, reduced order picking times, and integration with urban logistics systems. Thus, the identified scientific gap in the study of the network organization of micro-fulfillment as the final link in the e-commerce supply chain determines the relevance and scientific novelty of this article.

Aim and objectives. Aim of the research. To substantiate the feasibility of forming micro-fulfillment center (MFC) networks as an effective infrastructural solution for ensuring the stability, flexibility, and operational efficiency of quick e-commerce logistics under conditions of military threats and urban environment limitations.

Research objectives:

1. To investigate the specifics and challenges of quick e-commerce development in wartime conditions.
2. To analyze the role and functions of micro-fulfillment centers in the logistics infrastructure of urban areas.
3. To assess the potential of MFC networks in ensuring the adaptability of logistics in crisis conditions.
4. To identify key factors for the effective planning and location of MFCs.
5. To propose a structural and functional model of an MFC network as an infrastructural

response to the challenges of quick e-commerce in wartime conditions.

Research methodology. This research employs a comprehensive methodology combining systemic, analytical, and applied approaches to substantiate the feasibility of developing MFC networks in the urban environment as an adaptive element of logistics infrastructure under martial law. Firstly, a systemic approach is used to investigate the functioning of quick e-commerce as a complex logistics system responding to external challenges. The analysis focuses on the ability of MFCs to ensure the continuity, flexibility, and speed of delivery in urbanized spaces, especially during a crisis. Secondly, case study analysis of micro-fulfillment implementation in wartime conditions is applied, particularly using examples from Ukrainian cities where the restructuring of logistics routes, the reorientation of warehouses, and the launch of local hubs took place. Thirdly, cluster analysis methods, specifically the K-means algorithm, are used to model the potential location of MFCs, considering the spatial distribution of demand, population density, risk zones, and the availability of transport infrastructure. This interdisciplinary approach allows for covering both strategic and applied aspects of forming an adaptive logistics infrastructure based on micro-fulfillment networks.

Results, analysis and discussion. Quick e-commerce (Q-commerce) is a cutting-edge model of online retail focused on ultra-fast delivery of everyday goods within 10-60 minutes after order placement. It is based on the use of micro-fulfillment centers, dark stores, and in-house or partner courier services located in close proximity to consumers in cities. Unlike traditional e-commerce, which focuses on a wide assortment and centralized warehouses, q-commerce prioritizes speed of service, relying on digital technologies, automation, and accurate demand forecasting. This model is becoming increasingly popular in the context of urbanization and changing consumer expectations. According to research by M. Bogdanova, 30 new Q-commerce companies were registered in Western Europe in 2020. One of the most striking examples is Gorillas, which managed to achieve «unicorn» status (capitalization over $1 billion) in less than a year, indicating extremely high demand from investors and users for quick, flexible, and localized logistics solutions, and one of them, called Gorillas, reached unicorn startup status in just nine months [28].

Scientific sources indicate that the «last mile» model in Q-commerce fundamentally differs from traditional e-commerce: while classic e-commerce optimizes delivery by combining several orders on one route, Q-commerce ensures point-to-point delivery of each individual order, often by an individual courier operating within a narrow micro-district. This changes the requirements for logistics infrastructure, personnel, IT systems, and route planning approaches [29]. Thus, Q-commerce forms a new paradigm of urban logistics, in which speed, flexibility, and local presence become the main competitive advantages.

Summarizing the impact of quick e-commerce on the transformation of urban logistics infrastructure and the evolution of approaches to solving the last mile delivery problem, we have systematized the main challenges and opportunities of this process. This analysis allows for a deeper understanding of how speed, technological innovations, and changing consumer expectations affect urban space and logistics practices. The presented generalization (Fig. 1) reflects the complexity and interdependence of factors shaping modern urban logistics in the context of the rapid development of Q-commerce.

Thus, the main risks associated with the development of quick e-commerce and last mile logistics concern the overloading of urban infrastructure, increased congestion, emissions, and logistics costs, as well as a lack of investment in sustainable solutions. In the context of military risks, these problems become even more complex due to infrastructure damage, the destruction of transport networks, disruptions in resource supply, limited access to key supply chain links, and potential security threats to logistics facilities and personnel. In addition, during wartime, problems arise with economic instability, including a decrease in consumer solvency and an increase in the number of goods requiring delivery to combat zones, which demands additional resources to ensure delivery under such conditions

Figure 1 – Generalization of influencing factors, risks and development opportunities of last mile logistics in the urban environment

At the same time, opportunities are associated with the introduction of innovative service formats, digital technologies, micro-fulfillment centers, and new models of cooperation, which can increase delivery efficiency, improve service, and reduce the negative impact on the urban environment. In addition, in wartime conditions, MFCs can become critically important for ensuring delivery to areas where traditional logistics routes are disrupted, as well as for adapting to changing conditions and ensuring the sustainability of logistics systems in crisis situations.

In the context of these challenges and opportunities, the role of micro-fulfillment centers (MFCs) is particularly noteworthy. They are seen as a key element of an adaptive logistics infrastructure capable of ensuring prompt, sustainable, and efficient delivery in the context of the rapid development of quick e-commerce. The high density of orders, the need to deliver small batches of goods in the shortest possible time, and the need to reduce the burden on urban infrastructure and the environment – all of this necessitates new approaches to the organization of the "last mile." In this context, micro-fulfillment centers (MFCs) play a strategic role. According to the results of the study «Micro Fulfillment Centers (MFCs) – Global Strategic Business Report,» the global MFC market was valued at US$6.2 billion in 2024 and is projected to reach US$31.6 billion by 2030, growing at a compound annual growth rate (CAGR) of 31.1% from 2024 to 2030 [30].

According to the definition of foreign scientists, MFCs are small or medium-sized logistics facilities located near the consumer, which perform the functions of storing, sorting, picking, and preparing orders for shipment. Their location within urban areas allows for a significant reduction in delivery time, lower transportation costs, a decrease in the number of freight trips, and the integration of environmentally friendly vehicles, such as cargo bicycles or electric vehicles. Thus, MFCs are not only a response to logistics challenges but also a tool for improving the quality of consumer service, reducing the carbon footprint of logistics, the rational use of urban space, and supporting the sustainable development of urban mobility. Their implementation allows cities to better adapt to the needs of Q-commerce while maintaining a balance between economic efficiency, social expectations, and environmental requirements.

Let's compare micro-fulfillment with traditional fulfillment. Obviously, these two models differ significantly in scale, efficiency, and approach to e-commerce. Traditional fulfillment centers are large logistics hubs, usually located outside cities, focused on processing a large volume of orders and providing centralized storage and shipment of goods. They are efficient in terms of scaling, cost per unit, and inventory optimization but are less flexible in the context of fast delivery to the end consumer, especially in urban areas. Micro-fulfillment centers, on the contrary, are characterized by smaller sizes, decentralized location closer to the consumer, and the ability to process orders in real-time. They are better adapted to the requirements of quick e-commerce (Q-commerce), where the speed of order fulfillment – from several hours to one day – is critical. At the same time, micro-fulfillment has challenges, including a higher cost of maintenance per unit, limited storage space, and the need for accurate demand forecasting.

Table 1 presents the results of a comparative analysis of the main characteristics of fulfillment centers and MFCs as logistics infrastructure facilities for last mile delivery.

The comparative analysis in Table 1 allows for visualizing these differences, showing the strengths and weaknesses of each model, and helps in choosing the optimal infrastructural strategy depending on the business model, geographical location of customers, and the target service level.

Table 1. Comparative analysis of fulfillment centers and micro-fulfillment centers as online order processing centers

Characteristics	Fulfillment Center (FC)	Micro-fulfillment Center (MFC)
Location	Mostly outside the city or on its perimeter	In the city or very close to consumers
Size	Large (tens of thousands of m²)	Small (200-500 m² or up to 5000 ft²)
Main function	Complex processing of large batches of goods	Fast processing of small batches of orders for last mile delivery
Delivery time	From several hours to several days	15-60 minutes (express delivery)
Type of orders processed	Large, wholesale or combined batches	Small, individual e-commerce orders
Transport logistics	Delivery is carried out by freight transport over long distances	Easy last mile delivery (couriers, electric vehicles)
Automation	High level of automation	Partial automation or compact automated solutions
Service cost	Higher due to transport costs and delivery time	Smaller due to proximity to the consumer
Flexibility	Low: orientation towards large orders	High: adapt to rapidly changing needs
Environmental impact	More emissions due to long routes	Less emissions due to reduced transportation

Source: Summarized by the author based on [16, 17, 19, 20]

The main advantages of micro-fulfillment centers (MFCs) in the quick e-commerce and last mile delivery system in the urban environment can be substantiated through several important aspects:

1. Relatively lower initial investment needs. MFCs have comparatively low capital investment requirements as they are easily integrated into existing logistics and operational processes already used for order processing. This creates opportunities for small and medium-sized businesses by providing access to innovative logistics without the need for large upfront costs. Such flexibility makes MFCs attractive to entrepreneurs seeking to grow their operations without significant financial investments in new infrastructure.

2. Optimal space utilization. Since MFCs are usually compact in size, their location in close proximity to consumers allows for significantly more efficient use of available space. This enables retailers to store a larger volume of products per unit area compared to traditional warehouses or stores. Thus, businesses can significantly improve the efficiency of their premises, optimizing rental costs and ensuring better availability of goods for consumers.

3. High level of process automation. MFCs are typically equipped with modern technologies for automating order processing, which significantly speeds up these processes. A high level of automation reduces the time required for packaging and shipping goods, as well as lowers the probability of human errors. This increases operational efficiency and allows for faster and more accurate order fulfillment, which is critical in the context of quick e-commerce.

4. Customer convenience. Locating MFCs closer to end consumers creates opportunities for faster returns, refunds, and exchanges of goods. This is important as convenience in returning goods is a significant factor in customer loyalty. Therefore, MFCs can significantly increase customer satisfaction through a simplified procedure for returns and exchanges.

5. Accelerated last mile task completion. One of the main advantages of MFCs is their ability to deliver goods with minimal delays, as these centers are located directly in urban areas where consumers live. This allows for reducing delivery times and enables same-day or delivery within a few hours after placing an order. Such speed meets the demands of modern quick e-commerce,

where delivery time is critical for meeting consumer needs.

Thus, MFCs not only ensure prompt delivery in crisis conditions but also increase the flexibility, reliability, and resilience of the entire logistics system. They are becoming an important infrastructural response to the challenges of an unpredictable environment.

Since international experience and the results of scientific research confirm the feasibility and effectiveness of creating MFCs in the urban environment to accelerate the delivery of goods sold online at the last mile stage, it is necessary to develop a methodological approach to selecting locations and forming a network of such centers.

The selection of locations for micro-fulfillment centers (MFCs) should be based on the concept of distributed warehousing, which involves not the centralization of logistics capacities in one large warehouse but the formation of a network of interconnected small warehouses evenly distributed within the urban or agglomeration area. This approach makes it possible to reduce the time and distance of delivery to the end consumer, adapt logistics flows to the high density of the urban population, and ensure greater flexibility and resilience of the logistics system.

The main characteristics of an MFC network in the context of distributed warehousing are:

1. Geographical decentralization – the presence of several warehouses evenly distributed in key areas of the city or region, which allows reducing the «last mile» time and minimizing transportation costs.

2. Functional complementarity – each MFC in the network performs a specialized or redundant function (storage, picking, cross-docking), ensuring the overall adaptability of the system to demand fluctuations and changes in consumer behavior.

3. Digital integration – the unification of MFCs into a single information system for managing inventory, orders, and delivery routes, which ensures real-time process synchronization.

4. Scalability flexibility – the ability to quickly expand or contract the network depending on seasonal peaks, marketing campaigns, or changes in the demographic distribution of demand.

5. High adaptability to urban conditions – each element of the network is designed taking into account the limitations of the urban environment (traffic, building density, zoning, availability of parking spaces), which makes such a network practical for large cities.

6. Reduced environmental impact – due to the reduction of transport legs and the possibility of using environmentally friendly modes of delivery (electric transport, bike logistics), the MFC network contributes to the sustainable development of urban logistics.

We will apply the K-means algorithm to the design of an MFC network in the urban environment, which allows for clustering geospatial data, facilitating the determination of optimal locations for MFC placement [31, 32].

The K-means algorithm for forming an MFC network works according to the following scheme:

1. The number of clusters K is determined, which corresponds to the number of MFCs in the network.

2. K initial cluster centers are randomly selected – conditional locations for the MFCs.

3. Each demand point (e.g., order or customer) is assigned to the nearest cluster center based on geographical distance.

4. For each cluster, a new center is calculated – the geometric mean of the demand points within that cluster.

5. Steps 3-4 are repeated until stabilization – when the cluster centers no longer change.

The method is based on minimizing the sum of the squared distances between each observation and the center of its cluster, that is, the function:

$$\sum_{i=1}^{N} d\left(x_i, m_j(x_i)\right)^2$$

where d – is the metric (in our case, distance); x_i – is the i-th data object; and $m_j(x_i)$ – is the center of the cluster to which element x_i is assigned at the j-th iteration. In this case, the cluster center will be considered the branch that is geometrically closest to the actual center of the cluster obtained from the K-means calculations.

For the practical application of the K-means algorithm, data on the location of parcel delivery points and existing fulfillment centers of the «Nova Poshta» company in the city of Kyiv were used. The geographical coordinates of each point were determined using «Google Maps» and «OpenStreetMap» services. The obtained coordinates were clustered using the standard K-means algorithm.

To determine the optimal number of clusters, a search of values from 3 to 40 was performed. For each option, the value of the objective function of the following form was calculated:

$$F(n) = intera_n + C_{CENTER} * n$$

where:

$intera_n$ – is the clustering inertia, which reflects the quality of clustering by summing the squared distances between each point and its centroid. This parameter is calculated by measuring the distance between each data point and its centroid, squaring this distance, and summing these squares for one cluster;

$\mathrm{C_{CENTER}}$ – is the cost parameter for creating a new cluster. The value $\mathrm{C_{CENTER}}=0.01$ is set, which is due to the low absolute values of the distances between objects in geographical coordinates (due to the fractional part of longitude and latitude);

n – is the number of clusters.

The calculations were automated by writing a python script, and their results are presented in Fig. 2.

Thus, the smallest value of the objective function is achieved with the number of clusters equal to 14. This means that it is advisable to form 14 main centers that can act as MFCs for the 390 existing branches of the company. Further calculations are performed taking into account this number of clusters. The visualization of the clustering results is shown in Fig. 3. On the map, the branches of the "Nova Poshta" company are marked with dots, grouped by color according to their cluster affiliation. Branches that function as cluster centers are marked with framed dots.

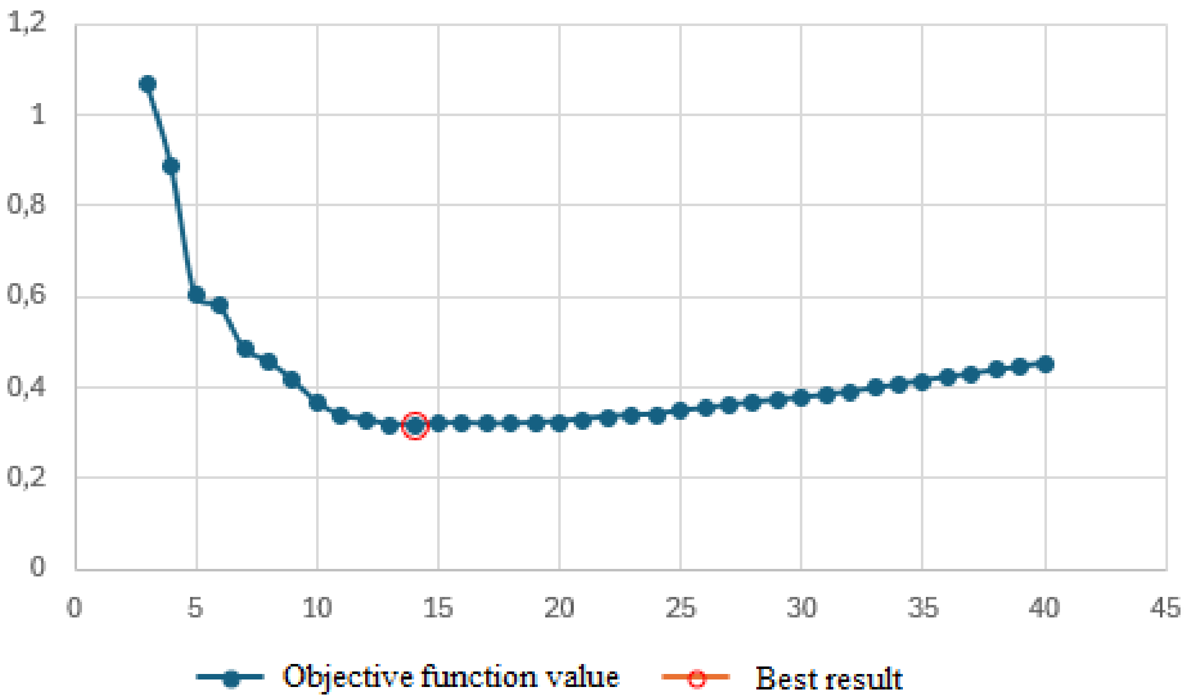

Figure 2 – Dependence of the objective function on the number of clustering points

Black lines show geographically justified connections between the central branches and their subordinate points.

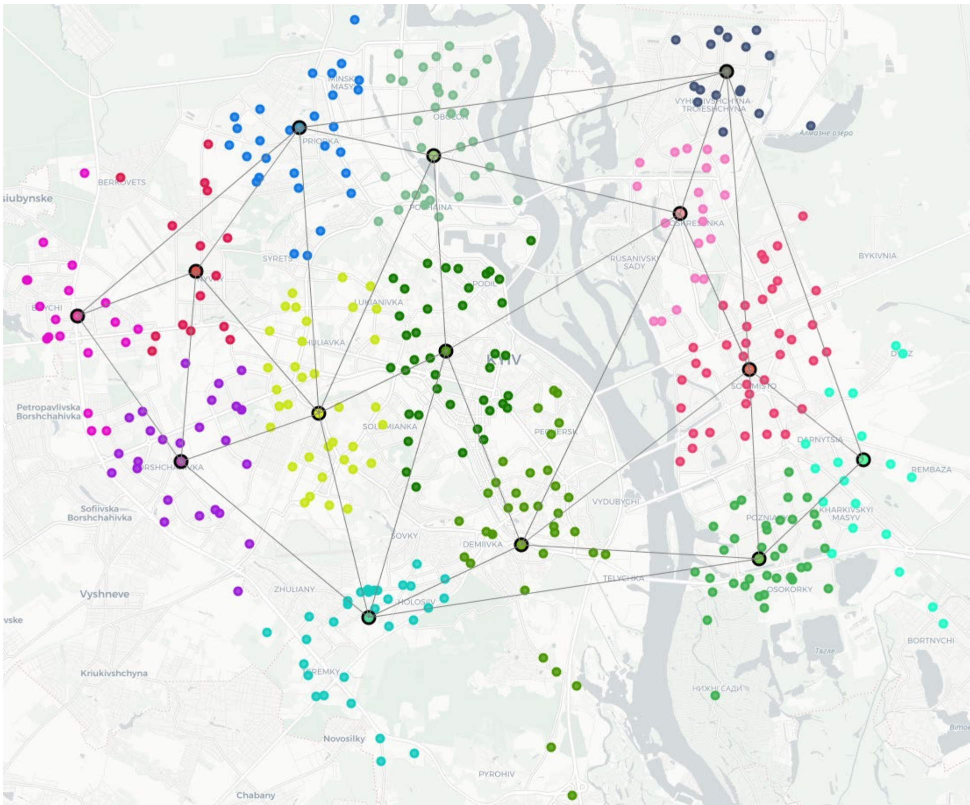

Figure 3 – Graphical representation of clusters and MFC localization points (number of clusters is 14)

Further, a detailed analysis of each of the identified clusters was conducted. For this purpose, appropriate calculations were performed for each cluster: the number of branches was determined (according to the results table obtained from the Python script), the average distance between branches within each cluster to its center was calculated, and the maximum distance from the center to the most distant branch was also determined. In addition, the table shows the coordinates of the centers of each cluster. The summarized calculation results are presented in Table 2.

The table shows that the average distance between branches in all clusters does not exceed 2.3 km, which indicates the compactness of the system. However, the main problem is the presence of local «tails» in cluster №8. Analyzing Fig. 3, it can be seen that cluster №8 (marked in light green at the bottom of the map) has an «elongated» shape along the Stolychne Highway, where five branches are quite far from each other and from other points in the cluster. A possible solution to this problem is to designate the northernmost branch as the «main» branch, which will speed up delivery to remote points. Theoretically, the number of orders at this branch will not be very large, as it will serve only a few branches, but this will reduce delivery time. For comparison, let's consider the results of the script for the case when the number of clusters is 26. The results are presented in Fig. 4.

It can be noted that most of the centers are located in the same location as the central branches of the clusters. It is also worth noting that with this number of clusters, the previously identified «problem» branches in the north are now combined into a separate cluster.

Table 2. Determination of MFC localization points in the network of parcel delivery points of the «Nova Poshta» company

Cluster number	Average distance (m)	Maximum distance (m)	Number of branches	X of the center	Y of the center
0	1666,81	4002,02	31	50,38572358	30,47109848
1	2011,31	5046,74	20	50,42511910	30,66494160
2	1935,34	3856,65	40	50,45232233	30,50143416
3	1821,72	4499,83	39	50,44775897	30,62026454
4	1585,85	3959,95	20	50,46104150	30,35731010
5	1710,54	3564,27	29	50,50806720	30,44406840
6	1349,53	3983,54	37	50,40046300	30,62392020
7	1130,91	2775,35	17	50,52201388	30,61130856
8	2239,00	7112,28	36	50,40395982	30,53104248
9	1559,38	3526,58	18	50,47223131	30,40372063
10	1724,12	3068,27	34	50,50095194	30,49676930
11	1775,98	3939,12	27	50,42474840	30,39773660
12	1971,83	3826,95	36	50,43670684	30,45182835
13	1534,27	3082,39	20	50,48662650	30,59304767

According to real data, there is also a cargo branch in this area. However, attention should be paid to significant discrepancies in the central areas of the city. In our model, 8 «main» branches are located there, while in reality, «Nova Poshta» has only 2 cargo branches. This may be due to the lower population density in these areas (data from Kyiv Statistics).

However, even with this population density, the creation of additional cargo and warehouse branches in the central areas can improve the logistics structure of «Nova Poshta». Even with the current lower population density in the historical center, existing forecasts of tourist flows and prospects for the development of dark-store formats suggest the emergence of additional demand for same-day delivery.

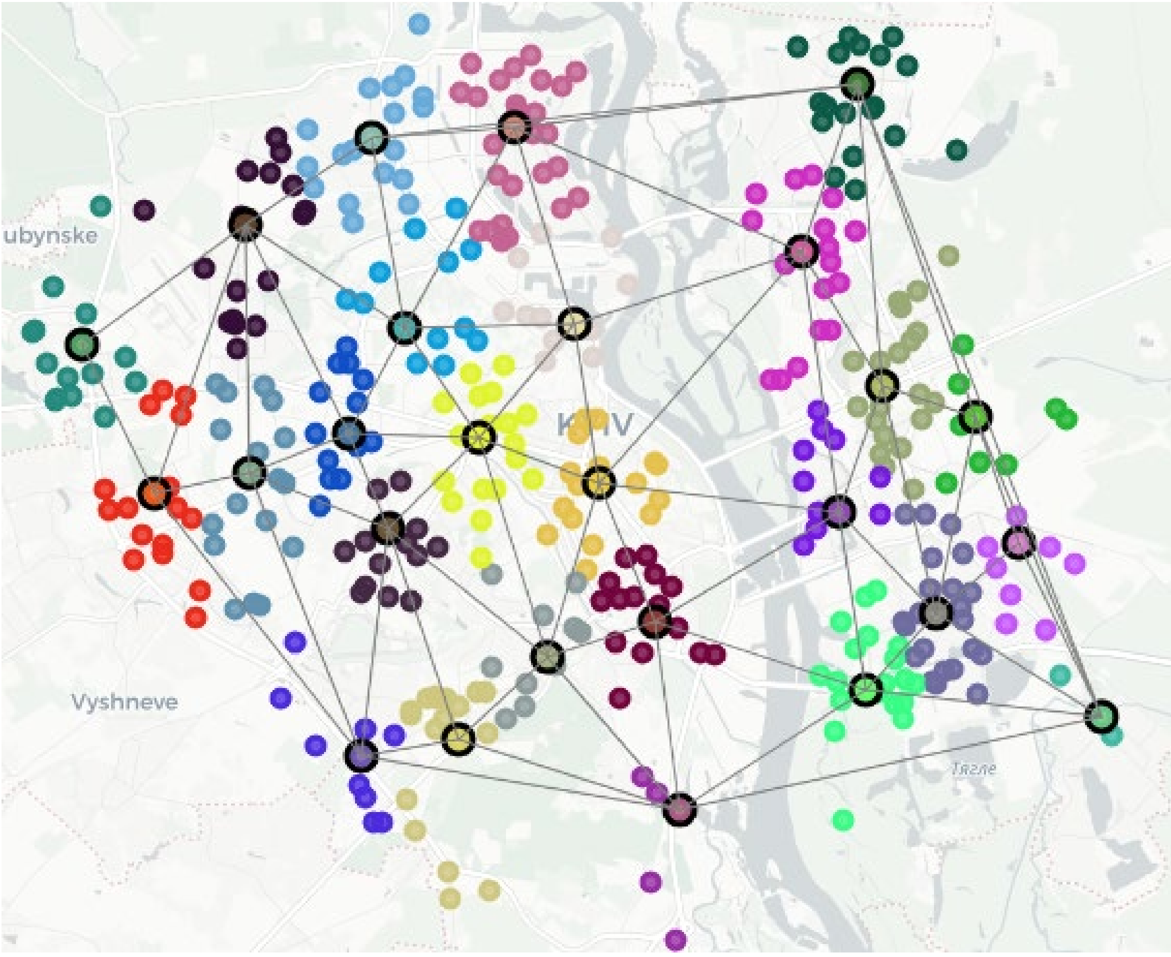

Figure 4 – Graphical representation of clusters and MFC localization points (number of clusters is 26)

The placement of two compact cargo and warehouse hubs (for example, underground parking lots or the renovation of non-residential premises) will reduce the average distance to < 1.2 km, which will reduce the number of «cross» trips between clusters № 0, 2 and 10. Modeling showed that if any of the 14 main branches are disconnected, the average distance increases by a maximum of 0.35 km, and the courier routing time increases by 6 minutes. This indicates a sufficient level of redundancy. The actual compactness of the network (d ≤ 2.3 km with 14 clusters and ≤ 2.7 km with 26 clusters) indicates significant investments by «Nova Poshta» in dense coverage. The problem is not the number of branches, but the local geometry of the network, when a group of branches located in a «snake pattern» moves away from the center.

Overall, the calculation results show that «Nova Poshta» has an efficient system with a sufficient level of redundancy, but for further improvement, it is necessary to make changes to the geometry of the branches' location and consider the possibility of creating additional warehouse points in key areas of the city.

Conclusions. As a result of the conducted research, the effectiveness of micro-fulfillment center (MFC) networks as an adaptive logistical response to the challenges of quick e-commerce in urbanized environments and emergency situations, particularly wartime conditions, was theoretically substantiated and practically confirmed.

1. It was established that quick e-commerce plays a key role in providing the population with essential goods, especially under conditions of limited functioning of traditional supply channels. The main challenges in the development of last mile logistics in wartime conditions (infrastructural limitations, security, demand instability, etc.) were identified, and it was shown that a network approach to the placement of MFCs allows for an effective response to them. The network approach using MFCs increases the resilience of the logistics system through decentralization and risk distribution, as well as sustainable development by reducing transportation costs, environmental impact, and energy consumption through the localization of warehousing and delivery.

2. The advantages of MFCs over traditional fulfillment centers were substantiated in terms of flexibility, delivery speed, spatial proximity to the consumer, and adaptability to local risks. MFCs typically have a compact format and can be quickly opened or relocated in response to changes in demand or security threats. This allows the logistics system to adapt to a dynamic environment, unlike large fulfillment centers that require significant time and resources for launch or relocation. The location of MFCs within the city or in close proximity to residential areas significantly shortens the «last mile» of delivery. This allows for order fulfillment within a few hours, which is especially important during crisis situations when the speed of supply is critical. MFCs can serve not only as logistical service points for commerce but also as elements of humanitarian infrastructure – for the distribution of basic goods, medicines, and essentials, especially in areas where large logistics facilities have been damaged or transport movement is limited.

3. Conceptual approaches to the formation of an MFC network using the K-means clustering algorithm for selecting optimal locations, considering the spatial structure of demand, were developed. Calculations were performed using the example of a specific network of parcel delivery points of a logistics company, which allowed for verifying the practical feasibility of implementing MFCs in the urban environment.

4. Further research on the development of MFC networks as an infrastructural response to the challenges of quick e-commerce in wartime conditions should focus on a deeper study of the role of digital technologies in ensuring the efficiency of logistics processes. This includes examining the impact of technologies such as artificial intelligence, big data analytics, process automation, and the use of the Internet of Things on improving the management of MFC networks, particularly in the context of adapting to changing conditions. Digitalization allows not only to optimize delivery processes but also to increase the level of resilience and flexibility of networks, which is extremely important in crisis situations such as war. The integration of the latest digital technologies into the logistics systems of MFCs can become a key factor in reducing costs, increasing delivery speed, and adapting to unstable conditions, which opens up new opportunities for the effective functioning of e-commerce in extreme situations.

5. The research results can be used by local authorities, e-commerce operators, logistics companies, and military-civil administrations for the rapid design and development of MFC networks in cities. The proposed approaches contribute to the optimization of the «last mile», ensuring access to essential goods in emergency situations, increasing response speed, and reducing the burden on the main logistics infrastructure. The use of spatial analysis tools allows for effective planning of local logistics hubs, taking into account needs of population and environmental constraints.

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