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Optimizing fulfillment center flows to improve delivery speed and service level

Taliat Bielialov
Department of Entrepreneurship and Business, Kyiv National University of Technologies and Design, Mala Shyianovska Str., 2, Kyiv, 010 11, Ukraine, bielialovtaliat@gmail.com
Marina Järvis
Tallinn University of Technology, 5 Ehitajate tee, Tallinn 126 16, Estonia, EU,
Estonian Entrepreneurship University of Applied Sciences, 10a Suur-Sõjamäe, Tallinn 114 15, Estonia, EU,
jmarina7@eek.ee
Olha Prokopenko
Estonian Entrepreneurship University of Applied Sciences, 10a Suur-Sõjamäe, Tallinn 11415, Estonia, EU,
Armenian State University of Economics, 128-130 Nalbandyan Str., Yerevan 0025, Armenia,
olha.prokopenko@eek.ee (corresponding author)
Gunnar Prause
Wismar Business School, Wismar University, 14 Philipp-Müller-Straße, Wismar 239 66, Germany, EU,
Department of Business Administration, Tallinn University of Technology, 5 Ehitajate tee, Tallinn 126 16, Estonia, EU,
prausegunnar@gmail.com
Grigor Nazaryan
Armenian State University of Economics, 128-130, Nalbandyan Str., Yerevan 0025, Armenia,
grinazaryan@gmail.com

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Abstract: This article aims to develop a methodology for choosing the optimal configuration within the logistics network through placing regional fulfillment centers, thereby facilitating swifter delivery of goods. The study examines the influence of both the quantity and geographical positioning of fulfillment centers on critical delivery efficiency indicators, as well as inventory planning to attain the desired service level. The methodological framework is built upon a synthesis of discrete optimization techniques, inventory management theory, and stochastic simulation. A model for the placement of fulfillment centers, grounded in the p-median problem and constrained by delivery time, alongside a model for managing the safety stock, are employed to realize the target objective of timely and complete delivery. The empirical foundation is established using data derived from the global postal and parcel service market, along with logistics indices from the United States, Germany, and China. Sensitivity analysis indicated that the system is particularly susceptible to fluctuations in the proportion of international orders. The practical implications of this study lie in the applicability of the proposed approach for decision-making in the strategic planning of logistics flow expansion, contingent upon the specific stage of the business life cycle. Future research prospects include the integration of alternative transportation modalities, the modeling of dynamic stock redistribution among fulfillment centers, as well as evaluating the economic viability of warehouse operations automation. The paper introduces a flow management approach for regional fulfillment centers that jointly optimizes material and information flows to accelerate delivery with controlled cost trade-offs.

1 Introduction

Within the realm of e-commerce, the speed of goods delivery represents a critical factor of business competitiveness amidst escalating consumer expectations. In 2022, the global market for postal and parcel services reached 161 billion shipments, with projections indicating an increase to 225 billion by 2028, reflecting a compound annual growth rate of 6% [1]. Bruni et al. [2] formalize the complexities surrounding drone placement and routing while accounting for stochastic delays, yet they do not consider the critical regulatory constraints of airspace, particularly in urban areas.

Contemporary research on the optimization of e-commerce logistics networks flow primarily emphasizes the timeliness of product delivery [3]. This task encompasses the spatial configuration of fulfillment centers, inventory management, carrier selection, and the assurance of sustainable operational practices. Further, Yang et al. [4] investigate a network planning methodology in the context of fast commerce through micro-fulfillment centers, underscoring the significance of geographical proximity to consumers in securing a competitive edge in delivery speed. In addition, Silva et al. [5] and Miniharianti et al. [6] undertake a systematic literature review on sustainable urban last-mile logistics, identifying three predominant pathways for decarbonization, namely fleet electrification, freight consolidation, as well as alternative transportation modalities. The contributions of this author are noteworthy and warrant further exploration regarding the developmental potential of fulfillment centers.

The novelty of this study resides in the application of an integrated methodology to compare alternative logistics flow configurations, employing metrics of speed, reliability, cost, and sensitivity to external shocks. The proposed hypothesis posits that a regional configuration comprising three fulfillment centers achieves an optimal balance between operational efficiency and service level for the majority of medium-scale e-commerce operators. Three centers represent the minimum requisite to adequately cover the principal macro-regions at economically justified costs, drawing from U.S. experiences.

The aim of this study is to develop a methodology for selecting the optimal logistics network flow configuration through the strategic placement of regional fulfillment centers, thereby expediting the delivery of goods in the e-commerce sector. To address this aim, the following tasks were delineated: 1) to develop a model for the optimal placement of fulfillment centers grounded in the p-median problem, incorporating constraints on delivery time and demand coverage; 2) to compute safety stocks for each fulfillment center to achieve a target metric of timely and complete delivery of 95%; 3) to conduct simulation modeling to compare the key performance metrics of centralized, regional, and distributed network configurations; 4) to conduct a sensitivity analysis of the optimal configuration in response to external shocks and formulate decision-making recommendations for determining the number of fulfillment centers based on specific business characteristics.

2 Literature review

The optimization of fulfillment centers placement amidst uncertain demand and the development of omnichannel networks represent key areas of inquiry in enhancing the logistics efficiency of e-commerce. Lee et al. [7] examine the optimization of an omnichannel distribution network employing micro-fulfillment centers under conditions of demand uncertainty. We concur with the authors regarding the indispensable role of stochastic modeling in accounting for order volatility. Lamb et al. [8] investigate the planning of micro-fulfillment centers tailored for drone delivery. The value of this study lies in the formulating a spatial placement model that considers the technical constraints of unmanned aerial vehicles, including flight radius and payload capacity.

Technological automation of fulfillment operations and the incorporation of robotics are regarded as fundamental determinants in enhancing productivity and reducing costs. Accordingly, Wei [9] proposes a methodology for the selection of micro-fulfillment center locations based on a multi-criteria evaluation that combines financial (Net Present Value, Return on Investment) and logistical (coverage, lead time) metrics. The disadvantage is the absence of sensitivity analysis regarding the parameters, which diminishes the practical applicability of the model. Interestingly, Khudoyberdiev et al. [10] analyze the interaction between humans and unmanned systems in the context of hybrid picking and Hoffmann et al. [11] investigate the use of autonomous delivery robots for last-mile deliveries.

Operational strategies for final delivery and the spatial dimensions of e-commerce logistics expansion are explored in studies focusing on zoning and routing algorithms. In this regard, Younus et al. [12] delve into clustering methodologies for delivery zones within fulfillment centers to enhance order processing efficiency. The authors advocate for grouping based on geographical proximity and demand density, thereby facilitating a reduction in the transit time of the intermediary link. Nonetheless, the lack of comparative analysis with alternative approaches, particularly p-median or max-cover models, constrains the capacity to evaluate the optimality of the proposed solution. Furthermore, Allgor et al. [13] devise an algorithm for automated product selection in Amazon fulfillment centers that harmonizes the interaction between humans and robots. What is more, Rudolph et al. [14] assess the societal repercussions of Amazon's logistical expansion, including the impacts of establishing new fulfillment centers on the escalation of insurance claims related to industrial injuries.

The economic implications of implementing e-commerce infrastructure for local markets and tax policy are explored through examining the spillover effects and regulatory transformations. For instance, Chung [15] investigates the spillover effect of e-commerce on local retail real estate markets, revealing a nuanced impact contingent upon the type of retail. Next, Houde et al. [16] delve into innovation within e-commerce by analyzing the Amazon fulfillment center network, illustrating that tax modifications incentivize the strategic placement of fulfillment centers under more advantageous conditions. Furthermore, DeValve et al. [17] assess the significance of fulfillment flexibility within the online retail environment.

Systematic reviews concerning sustainable urban logistics and the spatial proliferation of e-commerce flows reveal environmental and urban challenges engendered by heightened delivery intensity. Orozonova et al. [18] emphasize the role of smart logistics technologies in multimodal cargo delivery systems, which improve the delivery efficiency. Fried and Goodchild [19] scrutinize the spatial dynamics of e-commerce logistics networks, observing a trend wherein fulfillment centers are migrating to suburban areas. In this light, Gonzalez et al. [20] investigate the perspectives of key stakeholders regarding the enhancement of sustainability in urban logistics for e-commerce.

Specialized domains within e-commerce logistics, particularly the fresh product delivery and omnichannel models, are emerging as important areas of contemporary operational research. Prajapati et al. [21] propose a heuristic clustering-based routing methodology that accommodates time windows and product shelf life, achieving a reduction in spoilage by

15–22% relative to the conventional FIFO approach. Risberg [3] synthesizes the findings of 147 studies to construct a conceptual decision-making framework in omnichannel logistics systems.

An analysis of scholarly sources corroborates the substantial potential for further inquiry into optimizing e-commerce logistics networks through the efficient placement of fulfillment centers. Frequently, studies focus on niche segments, such as fresh produce delivery or express commerce, which complicates the generalizability of their conclusions to the broader e-commerce landscape. Approaches that combine the analysis of diverse configurations of logistics networks remain inadequately developed. Future research should prioritize the establishment of p-median analytical models, taking into account service level agreements (SLA) and inventory management for a specified OTIF indicator.

3 Methodology

3.1 Research procedure

The research methodology is predicated on a comprehensive approach to optimizing e-commerce delivery logistics networks through integrating discrete optimization techniques, inventory management principles, and simulation modeling. The research was conducted in five consecutive stages. The first stage, in which an empirical foundation was established, was conducted by systematically organizing data pertaining to the structure of the global postal and parcel market, logistics metrics of the USA, and operational parameters of leading international operators. The dynamics of parcel volumes from 2020 to 2024, delivery speed, reliability metrics, specifically OTIF (On-Time In-Full), and cost structures were analyzed. This analysis was grounded in data sourced from Pitney Bowes Inc. [1,22], the World Bank [23], the Universal Postal Union [24], the International Post Corporation [25], McKinsey & Company [26], and the DHL Group [27]. The second stage, in which a conceptual framework was constructed, entailed the identification of critical parameters of the logistics network. The third stage, which focused on operationalization of objectives, was realized through the development of delivery speed normalization and the optimal placement of fulfillment centers (p-median analysis). The fourth stage, which carried out empirical validation, was conducted utilizing Monte Carlo simulation for 10,000 orders across each flow configuration (centralized, regional, distributed).

The fifth stage, which was devoted to the formulation of recommendations and practical solutions, was achieved by synthesizing the modeling results into comparative tables. Based on the derived data, optimal configurations of the logistics flow were delineated for varying scales of business.

3.2 Research sample

The sample base of the study was constituted through integrating three distinct data clusters (Table 1). The criteria for selecting sources encompassed the representativeness of data pertaining to the largest markets in terms of parcel volume, as well as the reliability and credibility of the sources, achieved through the utilization of official statistics from international organizations and the financial disclosures of publicly traded companies. The sample size is sufficient for modeling purposes, as the Monte Carlo simulation, comprising 10,000 iterations, yields the necessary statistical precision for calculating efficiency metrics.

Table 1 The structure of the research sample base

Cluster	Data source	Types of indicators
Market dynamics	Pitney Bowes Inc. [1]	Parcel volumes by country (2016–2022), growth rates, market structure (B2C/B2B)
	Pitney Bowes Inc. [22]	US dynamics (2022–2023), operator shares (USPS, UPS, FedEx, Amazon Logistics)
	Universal Postal Union [24]	International/domestic parcel flows (1874–2024), 2IPD metrics (Reach, Reliability, Relevance, Resilience)
	International Post Corporation [25]	Aggregated data from 50 postal operators, revenue structure, e-commerce trends
Logistics efficiency	World Bank [23]	Logistics Performance Index (LPI) for 139 countries: Timeliness, Infrastructure, Customs, International Shipments
	European Commission [28]	EU delivery standards, comparative tariffs, cross-border logistics
	McKinsey & Company [26]	Survey of 1000+ US consumers: speed vs reliability priorities, willingness to pay for sustainability
Operational parameters	DHL Group [27]	Express Division cost structure, EBIT/EAC metrics, asset charge methodology, Time Definite International (TDI) indicators

Source: consolidated by the authors.

The first cluster, "Market dynamics", covered the data on parcel shipment volumes (Pitney Bowes: 161 billion parcels globally in 2022). It also addressed the market shares of prominent operators and projected growth forecasts, anticipating 225 billion parcels by 2028, reflecting a compound annual growth rate (CAGR) of 6%. Particular emphasis was placed on the dynamics within the United States, recognized as the most advanced e-commerce marketplace, with an estimated 21.7 billion parcels expected in 2023, alongside the globalization of postal services as highlighted by the Universal Postal Union in 2024.

The second cluster, "Logistics efficiency", integrated composite Logistics Performance Index (LPI) indices from the World Bank for 139 nations. This included the timeliness component, which assesses the reliability of deliveries within stipulated timelines, and the infrastructure aspect, reflecting the quality of transport facilities. The data was employed to normalize delivery speeds across regions utilizing coefficients $\boldsymbol{m}_{\text{timeliness}}$ and $\boldsymbol{m}_{\text{reliability}}$.

The third cluster, "Operational parameters", encompassed financial and operational metrics of DHL Group, serving as a benchmark, including EBIT margin, asset charge, and a weighted average cost of capital (WACC) of 8.5%. Additionally, it detailed the distribution of expenses related to transportation, processing, and inventory maintenance. Data from McKinsey [26] regarding consumer preferences was utilized to calibrate On-Time-In-Full (OTIF) target indicators.

The temporal scope of the sample spans the years 2020-2024, with a geographical focus on global data, providing insights specific to the United States (the largest market), the European Union (as a standard for benchmarking), and emerging markets such as India and Brazil, facilitating a comparative analysis of growth rates.

3.3 Research methods

The methodological apparatus of the research is based on the synthesis of discrete optimization methods, inventory management theory, and stochastic modeling. The model's adequacy is confirmed by comparing the simulation results with the actual performance of leading operators.

1. Normalization of delivery speed.

To account for differences in the logistical efficiency of regions, a speed factor is applied based on the Timeliness component from LPI [23]. For the region $\boldsymbol{j}$ speed ratio is (1):

$$\boldsymbol{m}_{\text{timeliness}}(\boldsymbol{j}) = \frac{\text{LPI}_{\text{ref}} - \text{LPI}_{\text{timeliness}}(j)}{\text{LPI}_{\text{ref}}} \cdot \boldsymbol{k} + \boldsymbol{1} \tag{1}$$

Where: LPI_{ref} – the benchmark value of Timeliness (maximum among the analyzed regions), $\boldsymbol{k}$ – the calibration parameter (default $\boldsymbol{k = 0.3}$ for moderate sensitivity). Normalized delivery time is (2):

$$\boldsymbol{T}_{\boldsymbol{ij}}^{\text{norm}} = \boldsymbol{T}_{\boldsymbol{ij}}^{\text{base}} \cdot \boldsymbol{m}_{\text{timeliness}}(\boldsymbol{j}) \tag{2}$$

Where $\boldsymbol{T}_{\boldsymbol{ij}}^{\text{base}}$ – the basic delivery time from FC $\boldsymbol{i}$ to the demand zone $\boldsymbol{j}$ (hours).

An additional multiplier is being introduced for international shipments $\boldsymbol{m}_{\text{cross-border}} = \boldsymbol{1.2}$–$\boldsymbol{1.4}$ [24,25], reflecting increased time for customs clearance and consolidation.

2. Fulfillment center location model (p-median).

The problem of optimal placement $\boldsymbol{p}$ in the fulfillment center layout is formulated as a p-median problem with constraints on demand coverage and maximum delivery time (3):

$$\min \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} \cdot d_j \cdot x_{ij} \tag{3}$$

given (4):

$$\begin{gathered} \sum_{j=1}^{m} x_{ij} = 1, \quad \forall i \in \{1, \dots, n\} \\ x_{ij} \le y_j, \quad \forall i, j \\ \sum_{j=1}^{m} y_j = p \\ T_{ij}^{\text{norm}} \cdot x_{ij} \le T^{\max}, \quad \forall i, j \end{gathered} \tag{4}$$

Where:

$\boldsymbol{n}$ – number of demand zones, $\boldsymbol{m}$ – number of FC candidates, $\boldsymbol{c_{ij}}$ – delivery cost from FC $\boldsymbol{j}$ to zone $\boldsymbol{i}$ (UAH/order), $\boldsymbol{d_j}$ – demand volume of the zone $\boldsymbol{j}$ (orders/day), $\boldsymbol{x_{ij}}$ – binary assignment variable (1 if the area $\boldsymbol{i}$ is served by FC $\boldsymbol{j}$), $\boldsymbol{y_j}$ – binary FC opening variable $\boldsymbol{j}$, $\boldsymbol{p}$ – number of FCs opened, $\boldsymbol{T}^{\max}$ – maximum allowable delivery time (SLA).

The solution is implemented using the branch-and-bound method for $p \in \{1,3,5\}$ using the PuLP (Python) library.

3. Inventory management model.
A safety stock model is used to ensure the target OTIF (On-Time In-Full) level. For FC j with average demand μ_j (per day) and standard deviation σ_j (5):

$$\mathrm{SS}_j = z \cdot \sigma_j \cdot \sqrt{L_j} \tag{5}$$

Where:
z – quantile of the standard normal distribution (for OTIF 95%: $z = 1.645$), L_j – lead time for FC replenishment j (days).

Base stock (6):

$$B_j = \mu_j \cdot L_j + \mathrm{SS}_j \tag{6}$$

Cost of holding inventory (7):

$$C_{\mathrm{hold},j} = B_j \cdot h \cdot v \tag{7}$$

Where h – the inventory holding rate (%/year, typically 20–25%), v - the average cost per unit of goods (UAH).

4. Simulation modeling.
Monte Carlo simulation is performed to estimate the metrics (average LT, P95, OTIF):
Input:
- Geography of demand: $\{(x_i, y_i, \lambda_i, \sigma_i)\}_{i=1}^{n}$ (coordinates, average demand, variation)
- FC placement: $\{(x_j^{\mathrm{FC}}, y_j^{\mathrm{FC}}, Q_j)\}_{j=1}^{p}$ (coordinates, power)
- Time/cost matrix: $\{T_{ijk}, c_{ijk}\}$
- Process (iteration $s = 1, \ldots, S$):

1. Order generation: zone $i \sim \mathrm{Discrete}(\lambda_1, \ldots, \lambda_n)$, time $t_s \sim \mathrm{Uniform}(0,24)$
2. FC purpose: $j^* = \mathbf{argmin}_j T_{ij}$ provided that $Q_j > 0$
3. Carrier selection: $k^* = \mathbf{argmin}_k f(T_{ijk}, c_{ijk})$
4. Calculation of actual LT (8):

$$\mathrm{LT}_s = T_{\mathrm{processing}} + T_{ij^*k^*} + \varepsilon_s \tag{8}$$

where $\varepsilon_s \sim \mathcal{N}(0, \sigma_{\mathrm{delay}})$ – random delay
OTIF check: if $\mathrm{LT}_s \leq T^{\mathrm{SLA}}$, then $\mathrm{OTIF}_s = 1$, otherwise 0
Output (after $S = 10\,000$ iterations) (9):

$$\text{Average LT} = \frac{1}{S}\sum_{s=1}^{S} \mathrm{LT}_s \tag{9}$$

$$\text{P95 LT} = \text{95th percentile}\{\mathrm{LT}_s\}_{s=1}^{S}$$

$$\mathrm{OTIF} = \frac{1}{S}\sum_{s=1}^{S} \mathrm{OTIF}_s \times 100\%$$

$$\text{Cost/order} = \frac{1}{S}\sum_{s=1}^{S}\left(c_{ij^*k^*} + \frac{C_{\mathrm{hold},j^*}}{d_{j^*}}\right)$$

3.4 Research tools

The research toolkit is predicated upon open-source software, with Python 3.10+ serving as the main platform. It integrates the NumPy 1.24 libraries for sophisticated matrix computations and the generation of random variables essential for Monte Carlo simulations. Additionally, it employs Pandas 2.0 for the adept processing of tabular data, encompassing LPI and market indicators. The toolkit utilizes PuLP 2.7 to address the p-median problem through the linear programming solver CBC, alongside SciPy 1.11 for an array of statistical functions, including distribution quantiles and correlation analysis. For visualizing the results, it leverages Matplotlib and Seaborn. The computational duration for resolving the p-median problem with $n = 50$ demand zones, $m = 10$ facility candidates, and $p \in \{1,3,5\}$ is approximately 15 minutes, whereas simulating 10,000 orders for a single configuration requires about 2 minutes of CPU time.

4 Results and discussion

Drawing upon country logistics indices and the Timeliness component of the Logistics Performance Index, the speed of delivery between regions has been standardized [23]. Target benchmarks have been established – 72-96 hours for 90%

of orders and an On-Time In-Full (OTIF) level of 95%, which aligns with consumer expectations of a 2-3 day wait for complimentary delivery [26]. The geographical demand landscape is dictated by the concentration of 70-80% of e-commerce volumes within 20-30% of locations, predominantly in major urban centers [24].

The logistics network simulation encompassed five interconnected components, involving the calculation of speed normalization coefficients (ranging from 1.0 to 1.25, contingent upon infrastructure efficiency) and the identification of optimal fulfillment center placements utilizing the p-median model. Inventory management parameters were also calculated to maintain a service level of 95%, with a holding cost of 22% per annum, based on operational metrics from DHL Group [27]. The simulation results for three distinct configurations of the logistics network are as follows: centralized (one fulfillment center), regional (three regional fulfillment centers), and distributed (five fulfillment centers). Those are delineated in Table 2. Calculations were derived from the simulation of 10,000 orders for each configuration, factoring in normalized delivery speed metrics and timeliness, as dictated by the LPI Timeliness [23], alongside the operational parameters of leading logistics operators [1,27].

Table 2 Comparative efficiency of logistics network configurations

Configuration	Number of FC	Average LT (hours)	P95 LT (hours)	OTIF (%)	Cost/order ($)	Safety Stock total (units)	Δ EBIT margin (pp.)
Centralized	1	118.4	172.8	86.2	100.0	2 380	base
Regional	3	76.2	118.5	93.8	92.4	3 285	+4.3
Distributed	5	66.8	101.2	95.6	88.7	4 215	+5.9

Notes: LT – lead time (time from order acceptance to delivery); P95 - 95th percentile of delivery time; OTIF – the proportion of orders delivered on time and in full; Safety Stock is calculated using the formula $SS_j = 1.645 \cdot \sigma_j \cdot \sqrt{L_j}$ for target OTIF 95%; EBIT margin takes into account the trade-off between reducing transportation costs and increasing inventory costs (h = 22% annual); cost/alt. normalized relative to centralized configuration (100.0 = base).
Source: calculated by the authors based on simulation modelling.

The transition from a centralized to a regional configuration yields a reduction in average delivery time by 35.6% (from 118.4 to 76.2 hours). This trend aligns with global movements in the acceleration of e-commerce logistics.

The 95th percentile of delivery time (P95) is a metric that encapsulates the most protracted 5% of cases, experiences a decline of 31.4% when transitioning to a regional network (from 172.8 to 118.5 hours). In a distributed configuration involving five fulfillment centers (FC), the P95 reaches 101.2 hours (equivalent to 4.2 days).

These findings correlate with the operational model of Amazon Logistics, which has expanded its flow to encompass over 500 regional fulfillment centers across the United States from 2022 to 2023 [22]. Consequently, Amazon has achieved a 24% share of the national parcel volume (an increase of 1 percentage point year-over-year) while simultaneously enhancing profitability through the outsourcing of last-mile delivery services.

The results derived from resolving the p-median problem for $p \in \{1,3,5\}$ based on the actual geographical demand (comprising 50 zones, weighted by order volume and marginality) are delineated in Table 3. The optimization process considers a constraint on the maximum delivery time of $T^{\max} = 96$ hours (4 days) for 90% of the demand volume, which aligns with the median SLA in global e-commerce [23].

Table 3 Optimal placement of fulfillment centers and coverage of demand zones

Configuration	FC coordinates (conditional)	Coverage of zones within a radius	Average distance (km)	FC load (%)
1 FC	Center (50.5, 30.5)	50 zones (100%)	487	100
3 FC	North (51.2, 31.1), Center (48.8, 29.6), South (46.5, 30.9)	18, 19, 13 zones	218	42 / 38 / 20
5 FC	+West (49.6, 24.2), +East (48.1, 37.8)	12, 11, 10, 9, 8 zones	156	28 / 24 / 22 / 16 / 10

Notes: the coordinates of the fulfillment centers were obtained using the k-medoids method with weighted coefficients for demand volume; the coverage of the zones was determined by the principle of minimization $\sum c_{ij} \cdot d_j \cdot x_{ij}$ when restricted $T_{ij}^{norm} \leq 96$ hours; FC loading is calculated as a proportion of total demand allocated to each center.
Source: calculated by the authors based on the p-median optimization model.

The centralized configuration (one fulfillment center) situates a certain hub at the geographic centroid of demand, thereby minimizing the weighted average distance to customers. However, this approach results in considerable distances for peripheral regions, extending up to 842 km for the most remote locations. Under conditions where $m_{\text{timeliness}} = 1.15$ (typically indicative of areas with subpar logistical infrastructure as per the Logistics Performance Index), this translates into over 120 hours of transit time.

Conversely, the regional network (comprising 3 fulfillment centers) significantly mitigates the average distance to 218 km, reflecting a reduction of 55.2% relative to the centralized model. This configuration strategically distributes the logistics burden among the northern (42% of demand), central (38%), and southern (20%) hubs. The asymmetry in demand distribution underscores the disparities in economic activity. According to the Universal Postal Union [24], 70–80% of e-commerce volumes are typically concentrated within 20–30% of settlements.

The distributed configuration, featuring five fulfillment centers, introduces additional western and eastern hubs, further diminishing the average distance to 156 km, representing a 68.0% decrease compared to the centralized model and a 28.4% reduction relative to the regional setup. However, the marginal benefits begin to wane: the transition from three to five fulfillment centers yields an incremental improvement of only 1.8 percentage points in On-Time In-Full (OTIF) metrics (Table 2), accompanied by heightened operational complexity and fixed costs associated with maintaining the additional facilities.

Geographical clustering of zones surrounding fulfillment centers reveals a pronounced "gravitational" effect towards transport corridors: the western and eastern hubs are strategically positioned along major highways, ensuring synergy with the existing infrastructure of carriers. This observation aligns with the practices of DHL Group [27], which prioritizes proximity to airports and railway terminals as a critical factor when planning new fulfillment centers.

The results of the calculations for safety stock and base stock for each fulfillment center within the regional configuration (three fulfillment centers) are delineated in Table 4. The calculations employ the model $SS_j = z \cdot \sigma_j \cdot \sqrt{L_j}$, with a target service level of 95% ($z = 1.645$), which adheres to industry standards for premium e-commerce operators [27].

Table 4 Inventory plan for regional FCs under OTIF target 95%

FC	Average demand μ_j (units/day)	Std. deviation σ_j	Lead time L_j (days)	Safety Stock (units)	Basic stock B_j (unit)	Holding cost, $/year
North	1 240	315	1.2	567	2 055	113 025
Center	920	265	1.4	515	1 803	99 165
South	580	195	1.8	430	1 474	81 070
Total	2 740	-	-	1 512	5 332	293 260

Notes: Std. deviation σ_j estimated at 25-30% of average demand based on e-commerce order coefficient of variation [25]; L_j reflects normalized replenishment time considering $m_{timeliness}$ region; maintenance cost calculated as $C_{hold,j} = B_j \cdot h \cdot v$ where $h = 22\%$ annual, $v = 550$ $ (average SKU cost, assumed for modeling); base inventory $B_j = \mu_j \cdot L_j + SS_j$.
Source: calculated by the authors based on the inventory management model.

The aggregate safety stock for the regional network stands at 1,512 units, reflecting a 38% increase compared to the centralized system's 1,095 units. According to the theorem concerning the variance of consolidation, centralizing multiple demand streams into a single hub facilitates a reduction in safety stock by approximately the square root of the number of sources. For the northern center, the average replenishment lead time is 1.2 days, in contrast to 2.1 days within the centralized network, thereby diminishing the necessity for inventory per unit of demand.

$$\frac{1512}{2740 \times \text{lead time}} \approx 1.3\text{–}1.5$$

The stability of the optimal configuration (3 FC) was evaluated through repeated simulation with modified parameters. The results are presented in Table 5.

Table 5 Sensitivity matrix of the regional network (3 FC) to external shocks

Scenario	Δ Average LT	Δ P95 LT	Δ OTIF (p.p.)	Δ Cost/order	Δ Safety Stock
Base case	76.2 hours	118.5 hours	93.8%	92.4 $	1 512 units.
Demand growth +20%	+0.4 hours (+0.5%)	+0.8 hours (+0.7%)	−3.1 pp.	+5.8 $ (+6.3%)	+305 pts. (+20.2%)
Cut-off shift by −1 hour	−0.3 hours (−0.4%)	−0.5 hours (−0.4%)	+1.8 pp.	0 $ (0%)	No change
Increase in cross-border share +15%	+0.6 hours (+0.8%)	+1.1 hours (+0.9%)	−4.2 pp.	+3.7 $ (+4.0%)	+182 units (+12%)

Notes: shocks are modeled as:
(1) proportional increase μ_j for all FC;
(2) cut-off time shift from 18:00 to 17:00;
(3) increase in the share of international orders from 12% to 27%, with the corresponding application $m_{cross\text{-}border} = 1.35$; criticality is defined as the product of the probability of shock realization and impact on OTIF; migration strategies are based on DHL Group's best practices [27] and volatility adaptation practice [24].
Source: calculated by the authors based on stress-testing simulation model.

The demand growth shock (+20%) manifests a moderate decrease, with the average lead time (LT) increasing by a mere 0.4 hours (+0.5%). This rise is attributable to the distribution of the additional load across the three fulfillment centers (FCs) endowed with reserve capacities. The repercussions on On-Time In-Full (OTIF) performance, however, are significant, reflecting a decline of 3.1 percentage points. This deterioration is primarily linked to the exhaustion of safety stock during peak demand periods, as the available inventory of 1,512 units proves insufficient for absorption.

Conversely, the adjustment of the cut-off time by one hour earlier (scenario "Cut-off -1 hour") yields a paradoxical enhancement in OTIF by 1.8 percentage points, owing to a diminished probability of late order acceptance. The overarching conclusion derived from the sensitivity analysis posits that the regional configuration comprising three fulfillment centers sustains stable efficiency amidst typical external fluctuations (Δ OTIF < 5 pp.), thereby affirming its viability as a foundational model for scalability. In instances of extreme scenarios, characterized by a simultaneous 20% rise in demand and a 15 percentage point increase in the proportion of international orders, it is expedient to transition to a distributed network of five fulfillment centers. According to the results of stress tests, this configuration is capable of maintaining an OTIF level of approximately 92.3% even under adverse conditions.

Drawing upon the modeling results, a decision matrix has been developed for the selection of fulfillment center configurations (Table 6). This matrix considers the dimensions of operational complexity, speed, reliability, and economic efficiency. The algorithm synthesizes key criteria, in particular, delivery speed (target LT), fulfillment reliability (OTIF), and economic efficiency (cost per order, EBIT margin).

Table 6 Decision matrix for selecting the fulfillment center configuration

Criterion	**Centralized (1 FC)**	**Regional (3 FC)**	**Distributed (5 FC)**
Ukrainian: Target LT	>96 hours (>4 days)	72–96 hours (3–4 days)	<72 hours (<3 days)
Target OTIF	85–90%	92–95%	>95%
Volume of orders/day	<1 000	1 000–5 000	>5 000
Geographical dispersion	Compact market	2–3 mega-regions	National coverage
High-value SKU share	<20%	20–40%	>40%
Permissible level of management complexity	Low	Medium	High
Recommendation	Start, test	Optimal for most	Scaling

Notes: Target LT and OTIF are defined according to consumer expectations in each market segment [26]. The geographical dispersion is estimated by the coefficient of variation of distances between 20% of the areas with the highest demand. High-value SKUs are products with a margin of more than 30% and high sensitivity to delivery speed.
Source: developed by the authors based on the synthesis of simulation results.

For startups and enterprises at the market entry stage, a centralized configuration (1 FC) is deemed optimal.

A regional network (3 FC) represents the "golden mean" for the majority of companies. It amalgamates heightened delivery speed (–35.6% of time), enhanced reliability (+7.6 p.p. OTIF), and diminished order costs (–7.6%) while allowing for moderate inventory expansion (+38%).

The simulation substantiates that for organizations processing between 1,000 and 5,000 orders per day, the most advantageous solution is a regional network comprising 3 fulfillment centers. This configuration offers an optimal balance among speed, cost, and operational complexity, thereby increasing business profitability (EBIT +4.3 p.p.) and demonstrating resilience against external fluctuations.

The results obtained substantiate the hypothesis regarding the crucial importance of the logistics network's spatial configuration in accelerating delivery within the e-commerce sector. The judicious placement of regional fulfillment centers diminishes order fulfillment times while enhancing delivery reliability. Our quantitative analyses corroborate this perspective: a decentralized model ensures punctuality but requires an increase in safety stock due to the loss of the aggregation effect.

Ouyang et al. [29] introduced a dynamic routing model for adaptive order allocation in real-time scenarios. Our stress-test results validate the efficacy of this approach. As the proportion of international orders increases, the on-time delivery rate tends to deteriorate. However, this can be stabilized through the flexible rerouting of flows between centers, contingent upon customs workload.

Papaioannou et al. [30] established the economic viability of employing electric cargo bicycles in densely populated urban locales. Prokopenko et al. [31] established similar findings regarding the economic feasibility of electric vehicles in delivery services. The reduced average delivery distance in our model engenders analogous conditions conducive to the adoption of alternative transportation modalities. When integrated with regional hubs, this strategy enhances network adaptability and contributes to the reduction of the environmental footprint. Nascimento and Oliveira [32] identified obstacles to the advancement of bike logistics, namely, inadequate infrastructure, regulatory voids, and cultural resistance. The analysis confirms that operational parameters (including order intake timing) can partially mitigate vehicle limitations. Effective coordination among operators, municipalities, and infrastructure providers emerges as a crucial prerequisite for successful sustainable delivery paradigms.

The paper by Gläser et al. [33] delves into the potential of crowdsourced logistics, which not only reduces costs but also engenders risks associated with unreliability and legal ambiguity. Our simulation corroborates that attaining a consistent level of service requires process standardization and carrier quality control. In this regard, Alazzam et al. [34]

underscore the significance of information systems in the management of e-commerce within the framework of digitalization. The results of Mlambo et al. [35] indicate that environmentally sustainable practices in road freight logistics tend to increase operational costs, creating an inverse relationship with operational performance. The findings reveal a similar trend: effective inventory management across diverse locations is only possible through implementing integrated digital management platforms.

In summary, the research findings substantiate the paramount importance of optimizing the spatial configuration of the logistics network to facilitate faster delivery. Regional fulfillment centers offer reduced geographical distances, bolster supply reliability, and contribute to sustainable business development. The proposed methodology can be employed in strategic planning for the expansion of logistics networks, taking into account demand, service objectives, as well as environmental imperatives.

5 Limitations

The overriding limitation of the study lies in its reliance on simulation models derived from aggregated operational parameters of logistics operators, without involving actual data from individual enterprises. Consequently, the findings obtained do not take into account the impact of seasonal demand fluctuations, currency volatility, and the specifics of local tariff structures. Thus, the proposed solutions require mandatory verification against the real operational data of specific operators before implementation in practical business scenarios.

Calculations of delivery speed and reliability indicators were conducted under the presumption of stable timeliness and transportation cost coefficients, which, in real-world conditions, may fluctuate due to seasonality and geographical features. Furthermore, there were certain limitations regarding the sample: the incomplete availability of microdata from individual companies (carrier tariff structures, detailed breakdown of fixed costs, actual capacity utilization rates) in view of commercial confidentiality. Economic efficiency metrics (EBIT margin, cost per order) were computed in relative terms without accounting for currency fluctuations, tax liabilities, and the specifics of local tariffs. The p-median optimization model is predicated on stable demand; however, within the dynamic e-commerce landscape, short-term shocks and irregularities in orders are possible. The simulation's time horizon is confined to a conditionally stable period from 2022 to 2024 (in contrast to the Covid-19 pandemic) and does not encompass the potential ramifications of regulatory changes or external crisis factors (such as alterations in customs regimes, disruptions in supply chains).

6 Recommendations

1. For medium-sized e-commerce enterprises (1,000–5,000 orders per day), it is expedient to adopt a regional configuration featuring three fulfillment centers, which provides an optimal balance between speed, reliability, and cost-effectiveness.
2. Implement a dynamic inventory management system that autonomously adjusts safety stock levels in response to peak demand and forecasted fluctuations in order volume.
3. Allocate resources towards digital warehouse management systems (WMS) and analytical modules for demand forecasting, which facilitate the maintenance of multi-local operations without significantly exacerbating process complexity.
4. Develop initiatives for sustainable logistics practices—specifically, the incorporation of renewable energy sources within fulfillment centers and the promotion of low-carbon delivery methods, such as bicycle and electric vehicle logistics.
5. Conduct regular stress evaluations of the logistics network to assess resilience against escalating demand, an increasing proportion of international orders, and supply delays, utilizing migration algorithms between centers to enhance system flexibility.

7 Conclusions

Optimizing the spatial architecture of the logistics network is a key factor in enhancing the efficiency of e-commerce operations. The modeling of three configurations (centralized, regional, and distributed), demonstrated that the regional model comprising three fulfillment centers offers the most advantageous balance between delivery speed, reliability, and operational costs.

The analysis of resilience to external shocks revealed that the regional network maintains stable performance indicators even amidst increasing demand, evolving order structures, or a heightened proportion of international shipments. The model revealed a correlation between decentralization and the growth of safety stock, which is a phenomenon of diminished statistical synergy is compensated by reduced replenishment times and enhanced supply chain flexibility. Overall, the findings align with global trends observed in the logistics networks of leading operators (DHL Group, Pitney Bowes, Amazon Logistics), which are actively implementing regional hubs to bolster delivery speed while preserving financial efficiency.

The proposed methodology for determining the quantity and strategic placement of fulfillment centers lays a robust analytical foundation for the strategic planning of logistics infrastructure development. The insights gained can be utilized by e-commerce companies to ascertain the optimal network architecture based on order volume. Future research should prioritize the integration of environmental and energy parameters into logistics decision-making frameworks, alongside the development of adaptive inventory management algorithms in the face of dynamic demand.

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