IMPROVING SUSTAINABILITY IN LAST-MILE LOGISTICS IN RETAIL AND SERVICE SYSTEMS

Vadym Derkach,[1] Jurgita Paužuolienė[2]

Klaipėda University (Lithuania)

ABSTRACT

This study develops and tests an applied framework for improving last-mile logistics sustainability in retail and service systems. A structured literature review of peer-reviewed studies (2019–2026; *n* = 35) is combined with directed content analysis and semi-quantitative coding. Six implementation practice groups are evaluated across eight indicators: emissions, resource efficiency, circularity, cost, responsiveness, integration, transparency, and retail/service applicability. Based on the evidence matrix, a phased scenario model is designed for an urban retail-service network handling 10,000 weekly deliveries. The results indicate that IoT-enabled real-time visibility, blockchain-based traceability, and route optimisation with warehouse-transport synchronisation generate the strongest multi-criteria effect. In the modelled transition from baseline to full implementation (S0–S3), weekly CO_2 emissions decrease by 36.9%, unit fulfilment cost decreases by 18.7%, and on-time delivery increases by 9.1%.

KEY WORDS: *last-mile logistics, sustainability, retail logistics, Logistics 4.0, scenario modelling.*

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Introduction

Last-mile logistics has become one of the most important fields in supply chain management, because this particular link shapes directly the consumer experience, while at the same time generating a large share of urban logistics emissions and costs. The growth of e-commerce, shortening delivery windows and increasing return flows strengthen the need to integrate warehousing, transportation and customer service processes into one sustainable management logic (Rajkiran, Almeida, 2024; Vincek et al., 2023).

The most recent literature shows that the balance between efficiency and sustainability is today associated not with a single technology, but with a combination of several practices: route optimisation, real-time visibility, traceability, reverse logistics and data-driven decision-making (Malik et al., 2026; Wong et al., 2023; Javed et al., 2024). At the same time, a practical problem remains: many studies analyse separate sectors or individual technologies, but fewer works provide a systematic and practically applicable model for retail and service systems.

It should additionally be noted that, in practice, organisations often face the question of implementation sequence: which measures should be implemented first in order to achieve a tangible sustainability effect without worsening service reliability. Therefore, this article seeks not only to review individual technologies, but also to substantiate a consistent, stage-based transformation logic suitable for real retail and service systems.

[1] Vadym Derkach – doctoral student, Department of Management and Economics, Faculty of Social Sciences and Humanities, Klaipėda University
Scientific field: ESG Development, sustainable technologies
E-mail: vadym.derkach@ku.lt

[2] Jurgita Paužuolienė – associate professor, Department of Management and Economics, Faculty of Social Sciences and Humanities, Klaipėda University
Scientific field: corporate social responsibility, sustainable development
E-mail: jurgita.pauzuoliene@ku.lt

The research question is how can the phased implementation of process synchronisation, digital visibility and traceability improve last-mile sustainability indicators in retail and service systems?

The aim of the article is to develop and empirically substantiate a practical model for improving last-mile sustainability in retail and service systems.

To achieve the aim of the research, the following objectives were addressed:

1. To systematise the theoretical assumptions and development directions of last-mile sustainability.
2. To carry out an empirical analysis of peer-reviewed scientific publications by applying directed content analysis.
3. To construct a practical scenario-based model with quantitatively assessable results.

Research methods: a structured review of scientific literature, semi-quantitative coding with scenario modelling, and sensitivity analysis.

1. Theoretical foundations of sustainable last-mile logistics

Studies on the green supply chain emphasise that sustainability must be assessed based on the 'triple bottom line' logic: environmental, economic and social aspects (Rajkiran, Almeida, 2024; Rusch et al., 2022; Ali et al., 2024). This logic is particularly critical in the last-mile stage, as this is where high order fragmentation, significant geographic dispersion, and high service level requirements converge (Tsymbal et al., 2023).

From an economic perspective, a key challenge remains the functional disconnect between warehousing and transport processes, which causes waiting times, reduces transport capacity utilisation, and increases unit costs (Leung, 2025). From an environmental perspective, critical issues include empty runs, overly frequent repeat deliveries, and uncoordinated return chains (Habazin et al., 2025; Marić et al., 2024; Arsenio et al., 2025). From the perspective of social sustainability and service quality, the 'last mile' becomes a test of consumer trust: delivery time, communication accuracy, ease of returns and transparent information about order status determine not only the customer experience but also long-term loyalty dynamics. Therefore, the sustainability of the 'last mile' must be understood as an integrated operational outcome that encompasses operational efficiency, service reliability and responsible management of environmental impact simultaneously (Elghomri et al., 2025; Rasshyvalov, Nurakhova, 2025).

The 'Logistics 4.0' concept emphasises that visibility and data integrity are essential prerequisites for smart management (Vincek et al., 2023; Aerts, Mathys, 2024; Kaštelan et al., 2024). The Internet of Things (IoT), artificial intelligence (AI), blockchain, digital twins, 5G connectivity and big data analytics help facilitate the transition from reactive to predictive management (Apruzzese et al., 2023; Hirata et al., 2024; Fareed et al., 2024). However, the literature consistently shows that the technologies themselves do not guarantee sustainability. Impact is achieved when they are implemented alongside process reengineering and the integration of responsibilities across the warehouse, transport, customer service and reverse logistics chains (Ebinger, Omondi, 2020; Elghomri et al., 2025). It is also important to emphasise the data management aspect: the more real-time data is integrated into 'last-mile' management, the greater the importance of high-quality data standardisation, access management and cross-organisational trust becomes. In practice, this means that the digitalisation of sustainable logistics cannot be viewed solely as an IT project; it requires a unified process architecture, a clear system of indicators, and the consistent strengthening of management maturity (Khan et al., 2022; Gürpinar, Gulum, 2025; Alkhodair, Alkhudhayr, 2025).

In order to transfer the theoretical concept of sustainability to the applied level, last-mile analysis must distinguish clearly how each dimension is manifested in operational indicators. The environmental dimension is usually operationalised through CO_2 emissions, energy consumption per order, the share of empty runs, and packaging waste reduction. The economic dimension is associated with unit cost, delivery productivity, transport load factor, and the cost of repeated deliveries. The social dimension includes the stability of work organisation, service reliability, the quality of customer information, and the accessibility of the return process (Leung, 2025; Habazin et al., 2025; Zaid et al., 2025).

The empirical literature increasingly emphasises that these dimensions should not be assessed separately. For example, route optimisation may simultaneously reduce emissions and costs, but the excessively aggressive shortening of delivery windows may increase operational pressure, employee turnover and error frequency. Similarly, blockchain traceability strengthens transparency and accountability, but without appropriate process integration it may create an additional burden of data administration. Therefore, at the theoretical level, it is justified to move from one-dimensional KPIs to a multidimensional evaluation logic, in which indicators are assessed as an interrelated system (Fareed et al., 2024; Hirata et al., 2021; Malik et al., 2026).

In the practical context of retail and service systems, this means that sustainability policy must be linked to a specific sequence of decisions:

1. Stabilisation of operational flows;
2. Strengthening of data visibility;
3. Integration of traceability and return cycles.

This phased implementation reduces the risks of transformation, and allows organisations to avoid a common mistake: implementing advanced technologies before processes and employee competencies are ready (Nasereddin, 2024; Hordieiev et al., 2025).

A review of the literature identifies several structural barriers that most commonly limit progress in the area of 'last-mile' sustainability. First, data fragmentation across warehouse, transport and customer service systems hinders the ability to make integrated decisions in real time. Second, insufficient process standardisation complicates comparative performance analysis across departments and partners. Third, organisations often fail to recognise the need for change management: technological solutions are implemented, but responsibility frameworks, competency models and incentive mechanisms are not reviewed (Ebinger, Omondi, 2020; Javed et al., 2024; Gürpinar, Gulum, 2025).

An additional obstacle is an imbalance in investment priorities. In practice, companies tend to invest more readily in 'visible' measures, such as package tracking applications or automated communication, but postpone core process integration solutions, such as warehouse shipment synchronisation and route planning. As a result, only partial benefits are achieved: the volume of data increases, but the quality of solutions does not improve sufficiently. This tendency is particularly pronounced in those organisations that work with a large heterogeneous shipment portfolio and do not have a unified order-prioritisation algorithm (Leung, 2025; Yang et al., 2023; Jia, 2025).

The implementation of sustainability also depends on the external ecosystem: the infrastructure of urban logistics, regulation, delivery zone rules, the network of alternative delivery points, and data-sharing standards. Therefore, from a theoretical perspective, it is purposeful to treat the last mile as an open socio-technical system in which company decisions, the maturity level of partners, and public policy instruments jointly determine the final sustainability outcome (Arsenio et al., 2025; Kaštelan et al., 2024; Tsymbal et al., 2023).

Based on the literature analysed, in this article last-mile sustainability is modelled as a three-layer system: 1) the operational layer (synchronisation and routes), 2) the data layer (IoT/AI/blockchain), and 3) the circular layer (returns and reuse).

The figure shows that sustainable last-mile logistics depends on the coordination of warehouse operations, transport, digital visibility technologies, and reverse logistics. When these elements are synchronised, organisations can reduce emissions and costs, while improving delivery performance and transparency.

2. Methodology and empirical results

The empirical analysis was based on a targeted sample of peer-reviewed scientific sources (n = 35), selected according to three criteria: a direct link to last-mile logistics, sustainability or circular logistics; methodological clarity; and practical suitability for retail and service systems. The sample included scientific articles and methodological works published between 2019 and 2026 that introduced the most recent theoretical and empirical developments.

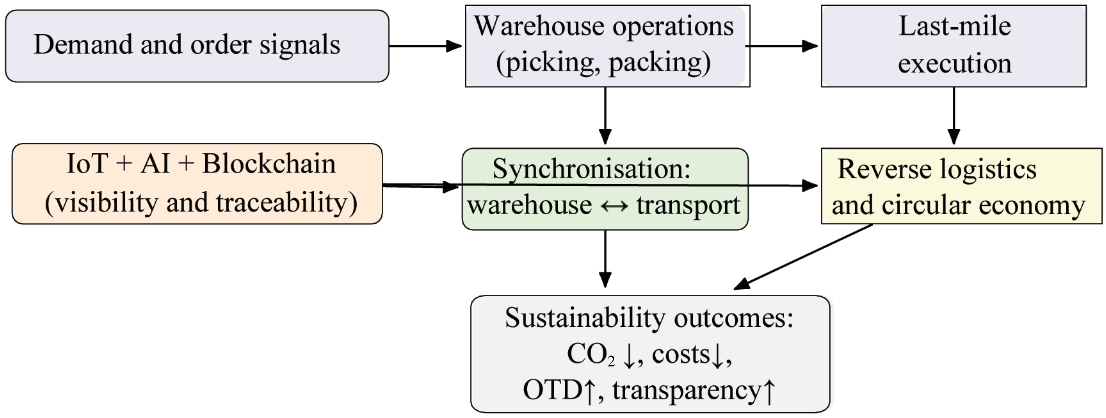

Figure 1. Integrated last-mile sustainability model for retail and service systems

Source: Compiled by the authors, based on research data.

The sample was not highly operationalised at the selection stage, that is, it was not linked only to emissions, costs, service level or traceability. This selection logic made it possible to preserve the comparability of the research result with the formulated research logic.

The empirical research logic consisted of four stages: corpus unification (text extraction, term standardisation), content analysis of statements and references, coding of key links according to predefined categories, and practical scenario construction and result interpretation. This design was selected because it allows the practical relevance of the identified patterns to be tested, rather than being limited to a narrative review (Hsieh, Shannon, 2005; Elo, Kyngäs, 2008; Mayring, 2014; Xiao, Watson, 2019).

After rule-based coding procedure was applied, six groups of practices were assessed:

1. Route optimisation and real-time planning.
2. Warehouse and transport synchronisation.
3. IoT-based real-time visibility.
4. Blockchain-based traceability.
5. Reverse logistics and circular logic.
6. Micro-hubs and alternative distribution channels.

Each practice was assessed according to eight indicators (emissions, resources, circularity, costs, responsiveness, integration, transparency, and applicability to retail/service systems). The coding logic was chosen because it allows one practice to be observed simultaneously in several effects, both as an environmental and as an operational or informational outcome.

Coding scheme, validation and practice score. The coding criteria were based on a strict rule-based procedure: for each document, statements were identified in which a direct link between logistics solutions and specific sustainability indicators was clearly established. This made it possible to avoid situations where documents are evaluated according to a general theme, without assessing direct interpretive argumentation.

In order to reduce the risk of subjectivity, three control principles were followed. First, a predefined set of coding practices and indicator definitions was used. Second, binary coding was applied: a direct and relevant link between the practice and the indicator existed, or did not exist. Third, interpretive triangulation was applied, that is, results were supported by combining bibliometric, review and case-based sources, so that conclusions would not rely on one type of publication alone.

The value applied for normalisation was:

$$S_{p,i} = 1 + 4 \cdot \frac{c_{p,i} - c_{min}}{c_{max} - c_{min}}$$

where cp,i is the number of documents in which a link between a practice and an indicator was identified. The integrated value of the practice was:

$$I_p = \frac{1}{8}\sum_{i=1}^{8} S_{p,i}$$

An additional sensitivity check was carried out using alternative weighting emphases (ecological priority and economic priority). Although the absolute magnitudes of the values changed slightly, the ranking of the highest practices remained stable (IoT visibility, blockchain traceability, route optimisation). This allows it to be stated that the obtained prioritisation is not a random result of a single weighting structure.

The results of the analysis show that the highest overall level of substantiation is demonstrated by IoT real-time visibility and blockchain traceability, followed by route optimisation. This is consistent with the most recent studies on logistics digitalisation and transparency (Malik et al., 2026; Hirata et al., 2021; Ebinger, Omondi, 2020; Jia, 2025).

Table 1. Average scores of practices (1–5) and practical priority

Practice	Ip	Strongest indicators	Priority
Route optimisation and real-time planning	4.37	Resource efficiency, costs, integration	High
Warehouse and transport synchronisation	3.01	Transparency, costs, responsiveness	Medium
IoT real-time visibility	4.60	Resource efficiency, costs, transparency	High
Blockchain traceability	4.32	Transparency, integration, traceability	High
Reverse logistics and circular flows	3.72	Circularity, costs, integration	Medium/High
Micro-hubs and alternative delivery	1.18	Fragmented evidence in analysed literature	Low

Source: compiled by the authors, based on research data.

The results also show the different function of practices within the overall sustainability architecture. The highest-rated practices (IoT, blockchain, route optimisation) function most often as 'horizontal infrastructure', which simultaneously improves several indicators. Meanwhile, medium-level practices (synchronisation, reverse logistics) more often have a 'vertical' effect: they are especially effective in specific processes, but less universal without the integration of additional solutions.

This distribution is important for the practical prioritisation of decisions: organisations should not interpret a lower score as lower strategic importance. For example, reverse logistics directly affects circularity and waste reduction, but its benefits become most apparent only when the basic infrastructure of data visibility and process synchronisation has been created.

In order for the empirical analysis to be practically applicable, a model implementation scenario was developed for a medium-size urban retail and service network (10,000 deliveries per week). Four scenarios were assessed. The scenario logic was designed to reflect the real transformation path of organisations: from basic operational stabilisation to more advanced integration of data and circular flows. In practice, companies rarely move directly to a full digital and circular model; therefore, a phased design allows intermediate results, investment priorities and risk profiles to be assessed more realistically.

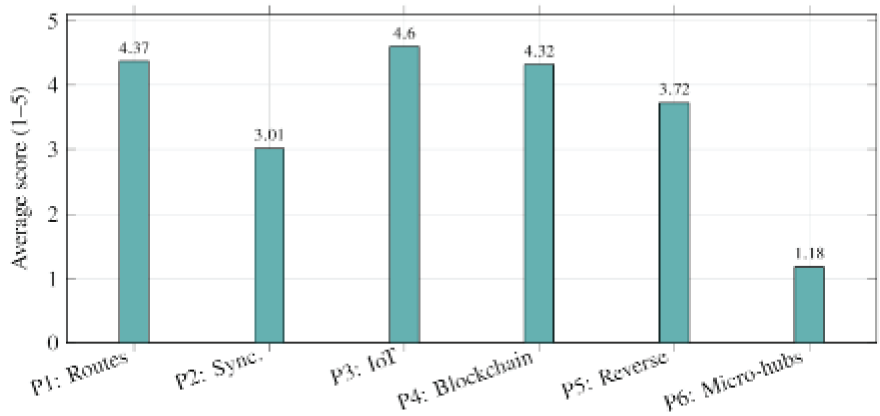

Figure 2. Practice scores based on empirical literature analysis

Source: compiled by the authors, based on research data.

The modelling of each scenario was based on three groups of assumptions: 1) operational assumptions (order density, route load, share of returns); 2) technological assumptions (level of visibility, planning frequency, traceability coverage); and 3) managerial assumptions (coordination of functions, discipline of data updating, prioritisation rules). This differentiation allows a clearer interpretation of why indicators change, not only because of technology, but also because of organisational discipline.

Table 2. The modelling of scenarios

Scenario	CO_2, t/week	Cost, EUR/order	OTD, %	Return cycle, days	Failed deliveries, %
S0 (baseline state)	22.5	5.40	87.0	6.4	9.2
S1	18.7	4.88	91.8	5.3	6.7
S2	16.1	4.63	94.6	4.7	5.1
S3	14.2	4.39	96.1	4.1	4.3

Note: S0 – current state (fragmented management); S1 – route optimisation + warehouse/transport synchronisation; S2–S1 + IoT visibility + blockchain traceability; S3–S2 + reverse logistics and circular flows.

Additionally, an integrated sustainability index was calculated:

$$SI = \sum_{k=1}^{6} w_k n_k \ ,$$

where *nk* are normalised indicator values, and the weights are: CO_2 (0.25), costs (0.20), OTD (0.20), return cycle (0.15), failed deliveries (0.10), data transparency (0.10).

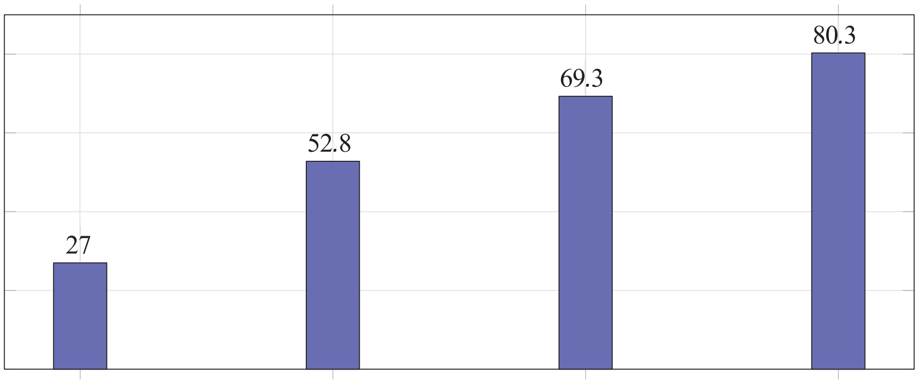

Figure 3. A sustainability index across the practical implementation scenario

Source: compiled by the authors, based on research data.

The results show that moving from S0 to S3 makes it possible to reduce weekly emissions by 36.9%, reduce the fulfilment cost per order by 18.7%, and increase the on-time delivery indicator by 9.1%. In addition, the model shows a consistent shortening of the return cycle, and a decrease in failed deliveries, which in retail and service organisations has a direct effect on customer satisfaction and the probability of repeat purchase.

In practical terms, this means that sustainability progress is achieved not through a single technological investment, but through a phased implementation path: process synchronisation – visibility/traceability – circular flows. From a managerial perspective, organisations are recommended to link each stage to clear control KPIs (OTD, share of repeat deliveries, route load, duration of the return cycle), so that investment return and sustainability progress are monitored not declaratively, but in an operational rhythm.

These results are consistent with broader studies on sustainable supply chains and digital transformation (Zaid et al., 2025; Fatorachian, Kazemi, 2025; Hordieiev et al., 2025; Tsymbal et al., 2023; Rusch et al., 2022; Rasshyvalov, Nurakhova, 2025), and provide a clearly implementable methodological basis for organisations.

Conclusions

The study conducted confirmed that last-mile sustainability in retail and service systems should not be understood as a question of implementing separate technologies. The most effective logic is integrated management, in which operational processes, data infrastructure and circular flows are developed as one coherent system. This approach makes it possible to manage not only emissions, but also service reliability, cost dynamics, and the quality of information provided to the customer at the same time.

The empirical analysis of peer-reviewed publications showed that the practices with the greatest multi-criteria impact are those that combine operational efficiency with data transparency: IoT real-time visibility, route optimisation and blockchain traceability. At the same time, medium-score practices, namely warehouse and transport synchronisation and reverse logistics, remain strategically necessary, because it is precisely these practices that create transformation stability, and the long-term foundation of circularity.

The results of the scenario model substantiate the benefits of phased implementation: moving from S0 to S3 demonstrated significant progress in environmental, economic and service indicators (CO_2, unit cost, OTD, return cycle, failed deliveries). In practical terms, this means that organisations should plan transformation consistently: first stabilising basic flows and coordination, then expanding visibility and traceability measures, and finally integrating circular return mechanisms.

The methodological contribution of the study is a replicable evaluation scheme, consisting of six practice groups, eight indicators, a normalised score, and a scenario index, which can be applied in different sectors or urban logistics contexts. The applied contribution is a clear decision-prioritisation model that allows organisations to link technological investment with tangible operational and sustainability returns.

The limitations of the study are related to the fact that the conclusions are based on a literature content analysis and modelling, rather than on long-term operational data from a single company. Therefore, in further research, it would be appropriate to carry out case studies of real organisations, supplement the model with sensitivity analysis for different levels of urban density and delivery profiles, and include a broader set of social impact indicators.

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PASKUTINĖS MYLIOS LOGISTIKOS TVARUMO GERINIMAS MAŽMENINĖS PREKYBOS IR PASLAUGŲ SISTEMOSE

Vadym Derkach, Jurgita Paužuolienė
Klaipėdos universitetas (Lietuva)

Santrauka

Paskutinės mylios logistika tapo viena svarbiausių tiekimo grandinės valdymo sričių, nes ši konkreti grandis tiesiogiai formuoja vartotojų patirtį, kartu lemia nemažą miesto logistikos išmetamųjų teršalų ir sąnaudų dalį. Elektroninės prekybos augimas, trumpėjantis pristatymo laikas ir augantys grąžinimo srautai didina poreikį integruoti sandėliavimo, transportavimo ir klientų aptarnavimo procesus į tvaraus valdymo logiką (Rajkiran, Almeida, 2024; Vincek ir kt., 2023).

Naujausia mokslinė literatūra atskleidžia, kad efektyvumo ir tvarumo pusiausvyra šiandien siejama ne su kuria nors viena technologija, o su kelių praktikų deriniu: maršrutų optimizavimu, matomumu realiuoju laiku, atsekamumu, atvirkštine logistika ir duomenimis pagrįstu sprendimų priėmimu (Malik ir kt., 2026; Wong ir kt., 2023; Javed ir kt., 2024). Vis dėlto išlieka praktinė problema: daugelyje tyrimų analizuojami pavieniai sektoriai arba individualios technologijos, rečiau pateikiamas sistemingas ir praktiškai pritaikomas mažmeninės prekybos ir paslaugų sistemų modelis.

Be to, reikėtų atkreipti dėmesį, kad praktikoje organizacijos dažnai susiduria su įgyvendinimo sekos klausimu: kurias priemones reikėtų įgyvendinti pirmiausia, kad būtų pasiektas apčiuopiamas tvarumo rezultatas nebloginant paslaugų patikimumo. Tad šiame straipsnyje siekiama ne tik apžvelgti konkrečias technologijas, bet ir pagrįsti nuoseklią, etapais pagrįstą transformacijos logiką, kuri tiktų realioms mažmeninės prekybos ir paslaugų sistemoms.

Straipsnyje keliamas probleminis klausimas: kaip etapais diegiant procesus, sinchronizuojant veiklas bei skaitmeninant matomumą ir atsekamumą, galima būtų pagerinti paskutinės mylios tvarumo rodiklius mažmeninės prekybos bei paslaugų sistemose?

Straipsnio tikslas: sukurti ir empiriškai pagrįsti praktinį paskutinės mylios logistikos tvarumo mažmeninės prekybos ir paslaugų sistemose gerinimo modelį.

Siekiant tyrimo tikslo, iškelti šie uždaviniai:

1. Susisteminti teorines paskutinės mylios tvarumo prielaidas ir plėtros kryptis.
2. Atlikti empirinę recenzuojamų mokslinių publikacijų analizę, taikant nukreiptą turinio analizę.
3. Sukurti praktinį scenarijais pagrįstą modelį su kiekybiškai įvertinamais rezultatais.

Tyrimo metodai: struktūruota mokslinės literatūros apžvalga, pusiau kiekybinis kodavimas modeliuojant scenarijus ir atliekant jautrumo analizę.

Šiame tyrime kuriama taikomoji mažmeninės prekybos ir paslaugų sistemų paskutinės mylios logistikos tvarumo gerinimo sistema. Struktūruota literatūros apžvalga, kurioje apžvelgiami recenzuojami tyrimai (2019–2026 m.; n = 35), derinama su nukreipta turinio analize ir pusiau kiekybiniu kodavimu. Šešios įgyvendinimo praktikos grupės vertinamos pagal aštuonis rodiklius: išmetamųjų teršalų kiekį; išteklių naudojimo efektyvumą; žiediškumą; sąnaudas; reagavimą; integraciją; skaidrumą ir mažmeninės prekybos / paslaugų pritaikomumą. Remiantis įrodymų matrica, sukurtas etapinis scenarijaus modelis miesto mažmeninės prekybos ir paslaugų tinklui, kuris apdoroja 10 tūkst. pristatymų per savaitę. Rezultatai atskleidžia, kad daiktų internetu pagrįstas matomumas realiuoju laiku, blokų grandinės pagrindu veikiantis atsekamumas ir maršrutų optimizavimas su sandėlio ir transporto sinchronizavimu sukuria stipriausią daugiakriterį efektą. Modeliuojant perėjimą nuo bazinio lygio prie visiško įdiegimo (S0–S3) savaitinis CO_2 išmetimas sumažėja 36,9 %, vieneto įvykdymo sąnaudos – 18,7 %, o pristatymas laiku padidėja 9,1 procentinio punkto.

Atliktas tyrimas patvirtino, kad paskutinės mylios tvarumo mažmeninės prekybos ir paslaugų sistemose nereikėtų suprasti kaip paskirų technologijų diegimo. Veiksmingiausia sistema – integruotas valdymas, kai veiklos procesai, duomenų infrastruktūra ir žiediniai srautai kuriami kaip viena darni sistema. Toks požiūris

leidžia vienu metu valdyti ne tik išmetamųjų teršalų kiekį, bet ir paslaugų patikimumą, sąnaudų dinamiką bei klientui teikiamos informacijos kokybę.

Sisteminė literatūros analizė atskleidė, kad didžiausią daugiakriterį poveikį daro praktikos, veiklos efektyvumą derinančios su duomenų skaidrumu: daiktų interneto matomumas realiuoju laiku, maršrutų optimizavimas ir blokų grandinės atsekamumas. Sandėlių ir transporto sinchronizavimas bei atvirkštinė logistika išlieka strategiškai būtinos, nes būtent šios praktikos lemia transformacijos stabilumą ir ilgalaikį žiediškumo pagrindą.

Scenarijų modelio rezultatai pagrindžia etapinio diegimo privalumus: perėjimas nuo S0 prie S3 atskleidė didžiulę aplinkosaugos, ekonomikos ir paslaugų rodiklių (CO_2, vieneto kaina, OTD, grąžinimo ciklas, nepavykę pristatymai) pažangą. Tai reiškia, kad organizacijos turėtų nuosekliai planuoti transformaciją: pirmiausia stabilizuoti pagrindinius srautus ir koordinavimą, tada plėsti matomumo ir atsekamumo priemones ir galiausiai integruoti žiedinės grąžos mechanizmus.

RAKTINIAI ŽODŽIAI: *paskutinės mylios logistika, tvarumas, mažmeninės prekybos logistika, Logistika 4.0, scenarijų modeliavimas*.

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