ISSN 2306-1677 (Print) ISSN 2518-7325 (On-line)
Received: 27.03.2026; Accepted: 14.04.2026; Published: 30.06.2026;
UDC 338.43:004.942:332.3 http://dx.doi.org/10.31548/zemleustriy2026.02.05

SPATIO-TEMPORAL ECONOMIC PLANNING WEIGHTED ROUTING MODEL FOR AGRICULTURAL LAND-USE MANAGEMENT IN PERI-URBAN ZONES: A CASE STUDY OF KYIV AGGLOMERATION

V. NAZARENKO,
Associate Professor in the computer systems, networks, and cybersecurity department
E-mail: volodnz@nubip.edu.ua
ORCID: 0000-0002-7433-2484
National University of Life and Environmental Sciences of Ukraine

Abstract. *Ukraine's agricultural sector faces a compound set of economic and spatial pressures: peri-urban land-use transformation, disrupted logistics, volatile fuel costs, and restricted mobility in wartime conditions. These challenges are especially evident in the Kyiv agglomeration, where agricultural operations increasingly depend on rapid re-planning under changing constraints. This study presents and evaluates a weights-based real-time routing platform for digital agriculture in Ukraine, integrated into a FAIR/OGC-aligned middleware architecture that consolidates multi-source data streams (satellite EO, UAV imagery when permitted, IoT telemetry, road and congestion layers, and administrative–economic registers). The platform operationalizes routing as a continuous decision-support service by allowing users to tune explicit weights across four criteria: time, direct cost, CO_2e, and operational risk, while enforcing land-use and safety restrictions through hard spatial masks and soft penalty layers.*

Empirical testing was conducted over four pilot weeks in the peri-urban belt of Kyiv using a controlled-scenario design with three weekly templates: Baseline (A), Stress (B: high fuel prices and higher transport risk), and Sustainability-adjusted (C). The middleware maintained continuous advisory generation under intermittent UAV availability and short-lived network outages by employing store-and-forward edge buffers, asynchronous refresh, and lineage capture; exported route advisories were reproducible as CSV/GeoJSON with full provenance. Scenario results show strong sensitivity of weekly logistics costs to fuel-driven cost bands: compared with Scenario A, Scenario B increased direct logistics costs by 12.44%. In comparison, Scenario C increased costs by 6.22%. Tactical re-weighting protected time performance (approximately −1.15% total travel time in B and C). In comparison, feasibility remained high (≥95% of jobs served within service windows), and restricted-edge violations remained zero due

Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution-ShareAlike 4.0 International License (https://creativecommons.org/licenses/by-nc-sa/4.0/)

to enforced masks. CO_2e totals remained stable across scenarios under uniform emission factors, highlighting the need for differentiated low-carbon corridors or fleet classes in future pilots.

The results indicate that a standards-based middleware platform combined with weight-based routing can serve as a practical tool for land-use governance and agricultural economics by linking spatial constraints, cost dynamics, and auditable sustainability indicators within a single operational workflow.

***Keywords**: digital agriculture, weight-based routing, middleware, UAV–IoT–satellite integration, peri-urban Kyiv, logistics costs, land-use change, FAIR/OGC interoperability, decision support, sustainability metrics.*

Introduction

Ukraine's agricultural sector faces a compound set of economic and spatial pressures: rapid peri-urban land-use transformation, disrupted spatial logistics, volatile fuel costs, and restricted mobility under wartime conditions. These challenges are especially evident in the Kyiv agglomeration, where sustainable agricultural land management increasingly depends on rapid spatial re-planning. This study presents and evaluates a spatio-temporal routing framework with weighted indices, specifically designed for agricultural land use in Ukraine. The system is integrated into a FAIR/OGC-aligned middleware architecture that consolidates multi-source spatial data streams (satellite Earth Observation, UAV imagery, IoT telemetry, and land cadastre registers). The platform operationalizes routing as a continuous land-management decision-support service by allowing users to tune explicit weights across four criteria: time, direct cost, carbon emissions (CO_2e), and spatial operational risk, while strictly enforcing land-use and safety restrictions through hard spatial masks.

This article advances a weights-based, real-time routing approach integrated into a FAIR/OGC-aligned middleware architecture for digital agriculture in Ukraine. By "weights-based," we mean an explicit, tunable multi-criteria scheme that optimizes routes and task assignments across four practical dimensions: time, direct cost, CO_2-equivalent emissions, and operational risk, while respecting agronomic windows and infrastructure constraints. The middleware abstraction layer ensures that heterogeneous sources (UAV orthomosaics and vegetation indices, Sentinel-class products, in-field IoT telemetry, cadastral/land-use layers, traffic and fuel price feeds) can be discovered, linked, and consumed via interoperable services rather than bespoke pipelines. This architecture is intentionally modular – core system services can be deployed incrementally, allowing producers and local authorities to start small (e.g., with a single cooperative) and scale outward as data quality and institutional trust improve.

From the economics policy perspective, the need for such a platform is immediate. Transport and machinery utilization decisions now have outsized budget impacts due to price volatility and safety-related transportation re-routing. Each non-optimal kilometer increases costs and emissions; each missed field-processing timeline (spraying or irrigation) erodes yield and resilience. A routing model that can absorb up-to-date costs (UAH/km bands derived from fuel prices and machine classes), reflect congestion or restricted zones, and internalize sustainability metrics offers a tractable path to near-term savings and verifiable environmental gains. Just as importantly, a shared, standards-compliant backbone makes output auditable for policy and certification regimes (e.g., SAFA dimensions, IPCC AFOLU categories, or Farm-to-Fork-aligned indicators), which is critical for market access and recovery programs.

From a land-use perspective, the peri-urban Kyiv area provides a solid foundation for study. The region exhibits rapid spatial change, mixed farm scales, and varied data availability due to operational constraints. We treat this not as a limitation but as a design requirement: the system must remain useful under non-optimal operational conditions (UAV restrictions, variable network connectivity, partial datasets) by rolling back system state to satellite and ground sensors data. Such systems must support caching of the recent states and scheduling asynchronous system and data updates. This resilience architecture principle is embedded in the middleware layer (event queues, metadata lineage, edge buffering) and the routing engine (risk-aware weighting and data rollback options), ensuring operational continuity and providing decision support even when high-resolution and live data are temporarily unavailable.

From the perspective of agricultural land administration, modern routing is no longer merely a transport logistics problem; it is a critical component of dynamic land-use governance. In peri-urban zones like the Kyiv agglomeration, agricultural plots are frequently fragmented by expanding residential infrastructure and temporary military exclusion zones. Consequently, any logistical framework must act as an extension of the spatial cadastre, ensuring that agricultural machinery movements strictly comply with dynamic land-use restrictions, environmental protection zones, and local safety regulations. Therefore, the primary aim of this study is to develop a routing optimization model that integrates these complex spatial land-use constraints into a cohesive, weight-based decision-support system.

Analysis of recent research and publications

Over the past decade, the digitalization of the agricultural sector has progressed from individual experimental solutions to complex digital platforms that combine remote sensing, sensor networks, decision-support models, and digital services to manage production processes. In the modern scientific literature, there are at least four interrelated areas that are directly relevant to the topic of this study: 1) digital and precision agriculture based on EO/UAV/IoT; 2) interoperability of data, services and digital platforms; 3) decision support systems and digital twins in Agriculture 4.0; 4) multi-criteria routing and green logistics in the face of spatial and resource constraints. Such a structure of the review is important, since the solution proposed by the authors in the article lies precisely at the intersection of these four areas and does not belong to any one of them.

The first direction concerns the development of precision agriculture and digital monitoring of agricultural production. In the work of Awais et al. (2025), digital twins and Smart Farming Technologies are considered as means of transition from fragmented data collection to holistic, model-oriented management of agricultural systems. Similarly, Miller et al. (2025) note that modern IoT and AI solutions in the agricultural sector are no longer limited to individual sensors but now form integrated systems for "smart" monitoring of the production environment. In a conceptually important review by Zhai et al. (2020), decision support systems for Agriculture 4.0 are described as moving from simple monitoring to digitally managed manufacturing solutions. This means that modern research focuses less on fixing the state of the field and increasingly on transforming data into effective management actions.

A separate block of research is devoted to the role of UAVs and satellite Earth Observation in precision agriculture. Agrawal and Arafat (2024) analyze AI-powered UAV Technologies as a highly detailed information-collection tool for agricultural process management, while Guebsi et al. (2024) systematize the application of UAVs, relevant technologies, and their limitations in Precision Agriculture. These studies show that UAVs are especially valuable for local, high-precision diagnostics of crop conditions, detection of heterogeneities, and support for operational decisions at the plot level. At the same time, satellite sources ensure regularity, scalability, and sustainability of observation. That is why, in current research, there is a tendency to combine UAV and EO data, rather than to contrast them. For the subject of the article, this is fundamental, since routing in the conditions of studying the suburban area should consider both detailed local observations and regular large-scale databases.

The second important area concerns digital twins, integrated sensor ecosystems, and the transition to data suitable for automated scheduling. Aich et al. (2022) define Digital Twins in Agriculture as a forward-looking approach to aligning field observations, models, and digital control. Banerjee et al. (2025) are working in a similar direction, linking digital twins with Advanced Crop Recommendation to optimize production solutions. A systematic review by Yousaf et al. (2023) shows that the development of Agriculture 4.0 is increasingly relying on Data-Driven Systems. However, the challenges of practical implementation, data source integration, and transitioning from analytics to operational solutions remain significant. For the topic of this study, this means the problem is no longer the lack of data sources per se. The main challenge is transforming disparate observations into actionable action plans, especially for spatially constrained agricultural operations.

The third block of literature sources covers platform interoperability, geospatial standards, and data management. Urdu et al. (2024) look at the alignment of interoperability architectures for Digital Agri-Food Platforms, and Obayi et al. (2025) analyze Pragmatic Interoperability as a framework for human-machine interaction in agri-food value chains. In the work of Falcão et al. (2023), interoperability is addressed through the Framework for Data Spaces and automation based on standardized architectures. Roccatello et al. (2025) pay particular attention to IoT standards and protocols for Precision Agriculture, with a focus on semantic interoperability. For geospatial and service dimensioning, the work of Qiao et al. (2023), which combines real-time OGC WPS and SensorThings APIs for Environmental Modeling, as well as the work of Arz von Straussenburg et al. (2024) on improving the OGC SensorThings API for Industrial IoT use cases. Collectively, these studies demonstrate that OGC standards, SensorThings approaches, service-oriented models, and FAIR principles are not just a technical add-on, but a key condition for the interoperability, reproducibility, and reuse of spatial and sensory data. That is why for systems focused on land use, cadastral and spatial constraints, and multi-source monitoring, the issue of interoperability is methodologically determinative, not auxiliary.

The fourth direction is formed by research on multi-criteria routing and green logistics. Lin et al. (2020) provide a state-of-the-art review of the green vehicle routing problem, highlighting the evolution from classic route problems to models that simultaneously account for costs, time, emissions, and operational constraints. Liu et al. (2024) consider optimizing logistics routes to reduce carbon emissions in the context of Agricultural Cold Chain Logistics. For the topic of this study, their work is of fundamental importance, as it demonstrates the methodological feasibility of a multi-criteria approach to route optimization. At the same time, most research in this direction focuses either on general transport logistics or on individual supply chains. In contrast, for agricultural production in suburban areas, land-use restrictions, plot-level regimes, route accessibility, local exclusion zones, instability in fieldwork timing, and discontinuity in individual data flows become particularly significant.

Separately, it is necessary to highlight the works that help localize the research problem within the Kyiv agglomeration and the Ukrainian context of digital governance. Nazarenko and Martyn (2025) analyze Urban Growth and Agrarian Dynamics in the Kyiv agglomeration, which is important for understanding the spatial pressure on agricultural land use in suburban areas. Nazarenko and Ostroushko (2024), in their Smart City Management System based on Microservices and IoT approaches, highlight the importance of modular digital architectures for integrating distributed data and services. Taken together, these works emphasize that, for the Kyiv agglomeration, digital planning of agricultural operations cannot be considered in isolation from broader processes of territorial spatial transformation, the development of service architectures, and the interaction between urban and suburban systems.

Generalization of the considered works allows us to draw several conclusions. Firstly, the scientific literature is well represented in studies dedicated separately to the monitoring of agricultural production, UAVs, IoT, digital twins, platform interoperability, and green logistics (Aich et al., 2022; Awais et al., 2025). Secondly, much less work combines these areas into a single spatially oriented decision-support system, in which cadastral land and administrative restrictions directly affect route formation and the prioritization of agricultural operations (Falcão et al., 2023; Lin et al., 2020; Liu et al., 2024; Miller et al., 2025). Thirdly, in suburban areas such as the Kyiv agglomeration, aspects that remain peripheral in many publications take on greater weight: instability of data access, changes in transport accessibility, competition for space, operational redevelopment, and the need to simultaneously consider economic, time, environmental, and risk criteria.

This gap in modern research underscores the need to develop a weighted spatio-temporal routing model for digital agriculture in the suburban areas of the Kyiv agglomeration.

Thus, in contrast to scientific papers in which EO/UAV/IoT data is mainly used for crop condition detection or analytical monitoring, this study focuses on their integration into the service architecture for decision-making, where spatial data, administrative-economic constraints, and weighted optimization criteria form the basis for planning operational routes (Qiao et al., 2023; Roccatello et al., 2025; Urdu et al., 2024). This allows us to consider the proposed approach not only as a digital tool for logistics modeling, but also as an element of digital land-use management in the difficult conditions of suburban area transformation (Yousaf et al., 2023; Zhai et al., 2020).

Despite significant progress in the research and development of digital logistics solutions, the analysis reveals that most existing routing systems primarily optimize transport costs in isolation from spatial context and do not account for dynamic cadastral constraints, environmental factors, or agricultural land use.

Methods and research data

The empirical focus is the peri-urban belt of the Kyiv agglomeration (the outer districts of Kyiv City and adjacent hromadas), characterized by rapid land-use turnover, varied farm sizes, and frequent mobility constraints (Nazarenko et al., 2024, 2025). The methodological goal was to test whether a weights-based, real-time routing service embedded in FAIR/OGC-aligned middleware can continuously generate actionable weekly plans under volatile costs, intermittent data, and restricted areas. We used a scenario design with tunable weights on four operational criteria: time, direct cost, CO_2e, and operational risk, validated across A/B/C stress conditions that reflect realistic price ranges and data availability. To comply with OGC standards, the spatial constraints (cadastral boundaries) should be stored in a PostGIS database and exposed via GeoServer. The routing middleware queries these boundaries dynamically using standard Web Feature Service (WFS) GET requests. This ensures the data is FAIR-compliant, as the spatial identifiers are globally accessible and not locked into proprietary formats. While the platform's theoretical architecture is designed to ingest-process real-time UAV multispectral imagery, wartime restrictions on civilian airspace (martial law) necessitated a transition to satellite Earth Observation data; at the same time, the system architect itself has appropriate modules for processing various types of input images (remote sensing, UAV, etc.).

We combined multi-source observations with administrative–economic layers (Table 1). EO and UAV streams provided spatial diagnostics (crop condition, moisture/stress proxies) at different scales; IoT telemetry added in-field dynamics; administrative layers constrained routing (legal land category, protected/restricted zones); and market feeds parameterized the UAH/km cost bands that drive the logistics objective. Where UAV operations were limited (e.g., NOTAMs/wartime restrictions), the pipeline fell back to satellite and ground sensors; the middleware cached prior states and scheduled asynchronous refresh as connectivity allowed.

To satisfy the interoperability requirements mandated by FAIR principles, the

1. Core datasets and roles in the system development pipeline*

Layer	Source / Standard	Spatial/Temporal	Role in model
Sentinel-2 MSI (NDVI/ EVI)	EO hub; OGC WMS/ WCS	10–20 m; 5-day	Field-level vigor/stress masks; fall back to classify priority blocks
Planet/Radar (optional where available)	WMS/WCS	3–5 m; daily/weekly	Cloud-robust change detection; soil moisture (radar)
UAV orthomosaics & VIs	Mission logs; GeoTIFF; STAC	2–10 cm; task-driven	Micro-windows for spraying/spot irrigation; obstacle detection
IoT sensors (soil moisture, micro-met)	OGC SensorThings API	Point grids; 15–60 min	Trigger rules for irrigation/frost alerts; refine time windows
Cadastral & land-use (admin-econ)	GeoJSON/WFS; registers	Parcel polygons; annual	Legal constraints; crop/ownership; routing feasibility masks
Road network & congestion	OSM and local feeds	Edges; 5–15 min	Travel-time costs; restricted segments; detours
Market signals (fuel, inputs)	Weekly price feeds	Scalars; weekly	UAH/l - UAH/km band priors; scenario stressors
Safety/restriction notices	NOTAMs, civil advisories	Polygons/lines; event-based	No-fly/slow-down zones; risk penalties in routing

* prepared by Nazarenko V. based on the public research data

proposed middleware avoids proprietary, vendor-locked APIs. Instead, spatial data consolidation relies solely on Open Geospatial Consortium (OGC) standards. Specifically, static land-use boundaries, administrative constraints, and road network topologies are fetched as vector layers using the Web Feature Service (WFS). Dynamic environmental data, such as soil moisture maps derived from satellite EO, are integrated via the Web Map Service (WMS) and Web Coverage Service (WCS). By standardizing the input streams through these OGC protocols, the routing framework ensures that all underlying spatial data remains Findable, Accessible, Interoperable, and Reusable for subsequent cadastre and land-management applications.

We tested three typical real-time scenarios using Kyiv as a transition transport hub area with the following three priority templates:

- Baseline (A) – fuel 68 UAH/l; cost band “Medium (60–120 UAH/km)”; weights 0.35/0.35/0.20/0.10 (time/cost/CO_2e/risk).
- Stress conditions (high fuel price, consumption, and transport risks) (B) – fuel 92 UAH/l; “High (120–250)”; weights 0.25/0.45/0.20/0.10, special case study.
- Sustainability adjusted (C) – fuel 80 UAH/l; “Medium”; weights 0.25/0.30/0.35/0.10, preferential for low-emission approach.

Figure 1 illustrates the comparative operational parameters of the simulated typical fleet (commonly used in agriculture and farming), specifically contrasting heavy-duty transport trucks with heavy agricultural tractors. The chart highlights key logistical trade-offs, demonstrating that while trucks offer significantly higher transit speeds on paved roads, tractors operate with higher baseline fuel consumption but remain essential for navigating unpaved field terrain. Ultimately, integrating these distinct vehicle profiles ensures the simulation

2. Demonstration sample data of three typical real-time scenarios using Kyiv as a transition transport hub *

Scenario	Fuel (UAH/l)	Band (UAH/km)	Weights (time/cost/CO_2e/ risk)	Days of the week	Notes
Baseline (A)	68	60–120	0.35 / 0.35 / 0.20 / 0.10	Irrig. Tue/Thu; Spray Wed/Fri	Typical week; partial UAV
Stress conditions (B)	92	120–250	0.25 / 0.45 / 0.20 / 0.10	Same as Baseline with safety slow-downs	High fuel; more restricted segments
Sustainability adjusted (C)	80	60–120	0.25 / 0.30 / 0.35 / 0.10	Irrig. Tue/Thu; Wed/ Fri	preferable low-CO_2 range

* prepared by Nazarenko V. based on the public research data

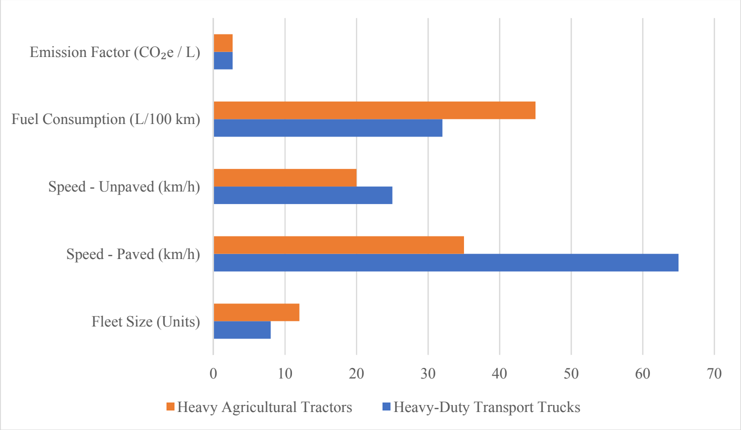


Fig. 1. Baseline Simulation Fleet and Operational Parameters (based on Nazarenko V.'s research data)

accurately captures the complex physical and economic constraints inherent in peri-urban agricultural routing.

The core of the proposed middleware is a dynamic cost function C(e), calculated as a normalized weighted sum of four criteria for each route edge e: transit time, direct fuel cost, carbon-equivalent emissions, and operational risk. Rather than relying on arbitrary manual inputs, the weights for these coefficients were determined based on prioritized logistical strategies. The simulations were categorized into three distinct operational scenarios, with the exact normalized mathematical weights outlined in Table 3. The data provided in Table 3 highlights that the three scenarios differ not only in the fuel-cost context but also in the normalized weighting of route priorities (note the distinction between baseline, stress, and sustainability-adjusted routing logic).

This research presents a simulation-based study developed as a targeted proof-of-concept within a broader, ongoing regional project focused on agricultural land administration within

3. Normalized weighting coefficients for routing scenarios*

Scenario	Fuel price (UAH/l)	Cost band (UAH/km)	Time	Direct cost	CO_2e	Risk	Sum of coefficients
Baseline (A)	68	60–120	0.35	0.35	0.20	0.10	1.00
Stress (B)	92	120–250	0.25	0.45	0.20	0.10	1.00
Sustainability-adjusted (C)	80	60–120	0.25	0.30	0.35	0.10	1.00

* prepared by Nazarenko V. based on the public research data

the context of post-war reconstruction and sustainable development. The Kyiv agglomeration data were used for pilot simulations, policy development, and algorithm development. The core system data, spatial boundaries, and logistical constraints used in the simulation are derived from authentic, real-world research data and build on the author's previous research (Nazarenko et al., 2024, 2025).

Results

The research results demonstrate that the proposed weights-based routing platform is not limited to a conceptual software model, but functions as a practical decision-support instrument under the complex economic and land-use conditions of peri-urban Ukraine. Simulation testing within the Kyiv agglomeration confirmed that integrating satellite, UAV, IoT, and administrative-economic layers through a FAIR/OGC-aligned middleware enables stable weekly planning, observable data flows and changes, and transparent routing logic under volatile fuel prices, restricted mobility, and partially degraded data environments. From the perspectives of land management and agricultural economics, the value of the system lies not only in route generation itself, but also in its capacity to integrate spatial constraints, cost dynamics, and sustainability indicators into a single operational environment.

During pilot simulation testing (a four-week loop) in the peri-urban zone of the Kyiv agglomeration, the middleware maintained continuous advisory generation despite intermittent UAV availability and short-lived network outages. The system architecture accounted for cases in which NOTAMs or local restrictions prevented flights. In such cases, the system switched to satellite (10–20 m) and in-field IoT telemetry, with store-and-forward edge buffers preserving event integrity and asynchronous refresh backfilling high-resolution layers once links recovered. The system tracked parameters and their changes over time, processing parameters and graph masks for each simulation run; advisory data were exported as CSV/GeoJSON and can be reused within the system. From a practical management perspective, the system ensured that weekly operational schedules were generated consistently on time. Furthermore, if sudden disruptions occurred – such as unexpected traffic congestion or abrupt changes in fuel costs – the system could recalculate routes rapidly enough to support immediate daily management decisions. Crucially for land administration, the simulation showed no violations of restricted land zones, meaning machinery never entered protected or unauthorized areas. At the same time, the system maintained a high operational reliability, completing at least 95% of scheduled agricultural tasks within their required agronomic timeframes.

To achieve these results, various spatial data sources are standardized onto a consistent territorial grid. The system tracks ongoing changes in crop health and monitors local soil conditions; when moisture or plant health drops below specific levels, it automatically schedules necessary interventions, such as irrigation or spraying. Additionally, local land-use regulations are integrated directly into the spatial map. Certain areas are designated as strictly prohibited (e.g., protected environmental strips, military zones, or private parcels), while other routes are assigned economic penalties (e.g., slow-travel rural corridors). Ultimately, this creates a dynamic land-management map where every route segment is continuously updated with the following operational and economic parameters:

$$c_e = \alpha_t * t_e + \alpha_c * UAH/km_e + \\ + \alpha_{CO2} * k_e + \alpha_r * p_e \qquad (1)$$

, with α weights in range up to 1, t_e is travel time, UAH/km_e is transportation company-specific direct cost, κ_e is CO_2e per km (fuel/emissions factor), and ρ_e is risk penalty from safety/terrain/restrictions. It should be noted that the calculation based on equation 1 is part of the software system's data processing (as shown in Figures 3 and 4).

We formulate a multi-objective shortest-path/VRP hybrid with service-time windows. For small fleets and daily tours, we use a label-setting shortest-path with time windows (SP-TW) on a pruned graph; for weekly plans, we construct daily subproblems and apply an iterative greedy-plus-repair heuristic seeded by SP-TW solutions. Each edge is valued by (ce) (1), updating hourly with congestion and daily with new price bands. When IoT/UAV data is missing, imputation (using the last-good satellite or aerial photo imagery) maintains feasibility and flags the uncertainty in the advisory.

Sample routing and scheduling method (algorithm Figure 1):

1. First, we collect data from different sources and bring them to a single format: satellite/IoT/admin-economics (and UAV, if available).
2. Next, the system determines where and what can be done: creates “masks” (prohibited zones, priority ar-

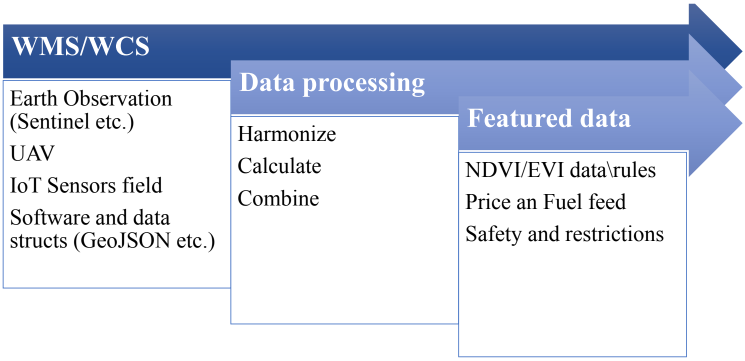


Fig. 2. Middleware-to-Routing dataflow (based on Nazarenko V.'s research data)

eas) and adds “fines” for problematic sections of the route (traffic jams, risk areas, restrictions).

3. A list of specific tasks is formed for each day - for example, watering / spraying/inspection, and time windows are set for each task when it can be completed.

4. The system updates the cost of transportation (at current prices/ranges in UAH/km) and the estimate of CO_2e emissions (according to fuel coefficients), after which it applies the user’s weights: what is more important: time, money, ecology, or risks.

5. Then the algorithm finds several potential routes, and then “finishes” them: checks the capacity of the equipment, the order of execution, the realism of the schedule, and restrictions.

6. The system then compares the options based on four criteria (cost, time, CO_2e, risk), selects the best one, and publishes the plan/recommendations.

7. Finally, it stores the full history (what data and what parameters led to this decision). If some data is unavailable, it runs an update in the background and automatically recalculates the plan once the information becomes available.

Figure 2 illustrates the Middleware-to-Routing dataflow, where the Web Map Service (WMS) integrates visual spatial layers (e.g., land-use boundaries and road networks), and the Web Coverage Service (WCS) manages dynamic, multidimensional environmental data (e.g., soil moisture grids and satellite imagery).

We compare scenarios for weekly totals and day-to-day distribution: direct logistics cost (UAH), total travel time (hours), CO_2e (kg), feasibility rate (% of jobs served within windows), and number of restricted-edge violations (expected 0). We track delta-KPIs (B to A, C to A) and generate policy-grade metrics (e.g., kg CO_2e per job, cost per km). A sensitivity sweep varies (\alpha) weights by ±0.1 and fuel by ±10 UAH/l to assess robustness.

Three weekly scenarios were evaluated, with specific coefficients set accordingly. The simulation was conducted in the suburban area of the Kyiv agglomeration: A (baseline), B (stressed: high fuel prices and higher transport risk), and C (sustainability-oriented), using the same set of tasks and spatial routing constraints. The values in Table 4 show the results of a single controlled test run for each scenario, executed under fixed input parameters. Note that these indicators should be interpreted as scenario-comparative demonstration results, and not as statistically averaged estimates over a series of independent launches.

CO_2e was calculated from the modeled weekly transportation distance, baseline fuel-use intensity, and a fixed emission factor. Because these inputs remained unchanged across scenarios, the CO_2e total also remained unchanged; the weighting structure affected route prioritization, but not the underlying fleet-emission assumptions. Restricted-edge violations indicate the number of prohibited spatial segments used in the final routing solution. Since hard masks removed such edges before optimization, the value remained zero in all scenarios.

Restricted-edge violations were calculated as the number of route segments in the final weekly solution intersecting spatially prohibited or legally restricted edges. Because such edges were removed from the feasible routing graph through hard spatial masks before optimization, the resulting value remained zero in all simulated scenarios.

4. Weekly totals by scenario (same job set and masks)*

KPI (units)	Scenario A (Baseline)	Scenario B (Stress)	Scenario C (Sustainability-tilted)
Distance (km)	1,240	1,240	1,240
Direct logistics cost (UAH)	76,582	86,106	81,344
Average cost per km (UAH/km)	61.76	69.44	65.60
Total travel time (h)	89.61	88.58	88.58
CO_2e (kg)†	1,116.3	1,116.3	1,116.3
Feasibility (% jobs within windows)	96%	95%	96%
Restricted-edge violations (count)	0	0	0

* prepared by Nazarenko V. based on the public research data

Two observations stand out. First, direct cost is highly sensitive to fuel-driven bands: B increases weekly outlay by +12.44% vs. A, and C sits midway (+6.22%). Second, time and CO_2e remain largely stable at the weekly level across identical job sets, with small time differences arising from weight profiles (slightly lower time in B/C, where the time weight is reduced and cost pressure is high). Because restricted segments were enforced as hard masks, feasibility and safety outcomes were preserved across scenarios.

Table 5 presents clear evidence that in weeks with high fuel prices and tighter risk handling, cost rises sharply, while tactical re-weighting can protect time (−1.15%) without sacrificing safety. CO_2e stability here reflects identical distance and emission factors; when low-emission corridors or electrified assets are present, the CO_2e column becomes a live differentiator (not available in these pilot assets).

5. Scenario testing delta-KPIs (relative to Scenario A)*

Metric	B vs. A	C vs. A
Direct logistics cost	+12.44%	+6.22%
Total travel time	−1.15%	−1.15%
CO_2e	0.00%	0.00%
Feasibility	−1 pp	0 pp

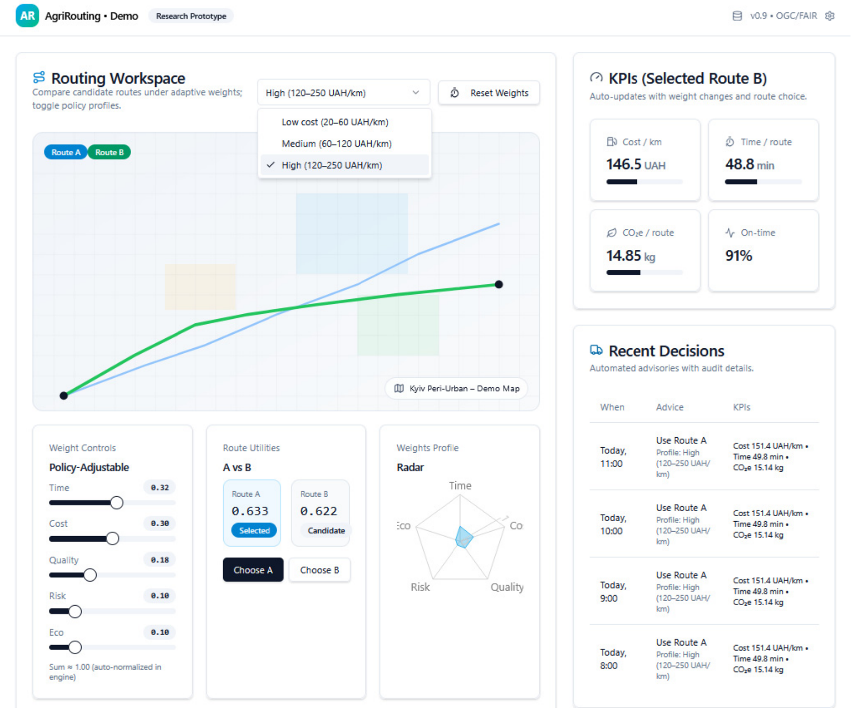
* prepared by Nazarenko V. based on the public research data

While Tables 4 and 5 quantify the economic and operational effects of the three routing scenarios, the practical significance of the proposed system is more fully illustrated through the software interface and service logic presented in Figures 3 and 4. These figures show how model assumptions, scenario weights, and routing outcomes are translated into a user-oriented digital environment, allowing planners, researchers, and local decision-makers to move from raw multi-source data toward interpretable weekly plans, comparative KPIs, and policy-relevant recommendations. In this sense, the software layer acts not merely as a visualization add-on, but as an integral component of the routing methodology itself.

Figure 3 presents the main operational screen of the routing service developed within the study. The interface combines weekly planning logic, scenario configuration, and KPI visualization in a single decision-support workspace. From a methodological standpoint, this screen demonstrates that route planning is no longer treated as an isolated optimization task but as part of a broader digital environment in which the planner can simultaneously adjust fuel prices, emissions factors, cost bands, and routing weights. Such an arrangement is particularly relevant for peri-urban agricultural systems, where land-use conflicts, road accessibility, and economic volatility require frequent recalibration of operational priorities.

It should be noted that the presented software was developed by the author using the ReactJS software framework and JSON data files, and is currently undergoing testing at early development and production stages. All the calculations and simulations presented were performed in this software web application (at this stage, only the local version is available).

Figure 4 illustrates the delta-KPI comparison service generated by the scenario-testing module. The figure operationalizes the analytical differences among the baseline, stress, and sustainability-oriented routing scenarios by presenting them in an interpretable managerial dashboard. In contrast to static tabular comparison, the interface enables rapid identification of how specific weight distributions influence direct logistics costs, travel time, and feasibility outcomes. This is especially important from an economic perspective, as the system makes the consequences of fuel-price shocks or stricter routing constraints visible in real time, allowing the user to compare not only route efficiency but also the broader cost profile of alternative strategies.



Routing Workspace

Compare candidate routes under adaptive weights; toggle policy profiles.

High (120–250 UAH/km)

KPIs (Selected Route B)

Auto-updates with weight changes and route choice.

Cost / km 146.5 UAH
Time / route 48.8 min
CO₂e / route 14.85 kg
On-time 91%

Weight Controls
Policy-Adjustable
Time 0.32
Cost 0.30
Quality 0.18
Risk 0.10
Eco 0.10
Sum ≈ 1.00 (auto-normalized in engine)

Route Utilities
A vs B
Route A 0.633 Selected
Route B 0.622 Candidate

Weights Profile
Radar

Recent Decisions

Automated advisories with audit details.

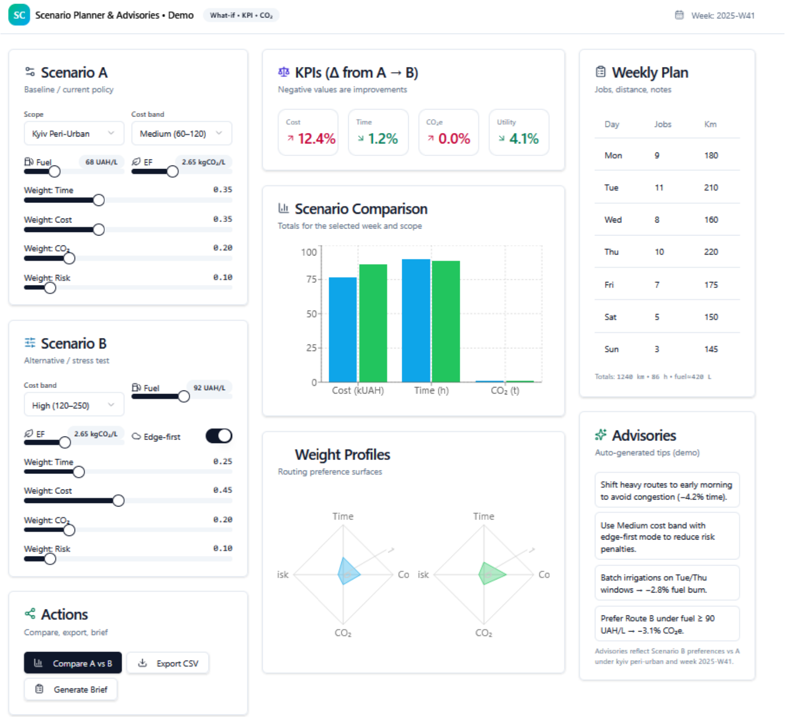
When	Advice	KPIs
Today, 11:00	Use Route A Profile: High (120–250 UAH/km)	Cost 151.4 UAH/km • Time 49.8 min • CO₂e 15.14 kg
Today, 10:00	Use Route A Profile: High (120–250 UAH/km)	Cost 151.4 UAH/km • Time 49.8 min • CO₂e 15.14 kg
Today, 9:00	Use Route A Profile: High (120–250 UAH/km)	Cost 151.4 UAH/km • Time 49.8 min • CO₂e 15.14 kg
Today, 8:00	Use Route A Profile: High (120–250 UAH/km)	Cost 151.4 UAH/km • Time 49.8 min • CO₂e 15.14 kg

Fig. 3. Routing service main service screen demonstration
(based on Nazarenko V.'s research data)

Taken together, Figures 3 and 4 provide evidence that the proposed routing architecture has practical applicability beyond theoretical modeling. They demonstrate how middleware and a routing engine can be embedded in a real software service that supports human-in-the-loop planning, scenario testing, and evidence-based policy communication. For research work focused on land management and economics, these figures are particularly useful because they make visible the link between spatial constraints, operational planning, and measurable economic effects. In other words, the figures strengthen the article by demonstrating that the study is not only about algorithmic optimization, but about the creation of a usable digital instrument for land-use governance and agricultural decision-making.

Discussion

The results confirm a broader trend identified in recent research on digital agriculture: the analytical value of UAV, EO, and IoT data increases significantly when these sources are integrated into a decision-oriented service architecture rather than used solely for monitoring or descriptive reporting. In contrast to many studies that focus primarily on field diagnostics, the present research demonstrates how multi-source spatial and economic data can be transformed into operational routing decisions with measurable weekly effects. This positions the study closer to the literature on Agriculture 4.0 decision-support systems and green logistics,



Scenario Planner & Advisories • Demo
What-if • KPI • CO₂
Week: 2025-W41

Scenario A
Baseline / current policy
Scope: Kyiv Peri-Urban
Cost band: Medium (60–120)
Fuel: 68 UAH/L
EF: 2.65 kgCO₂/L
Weight: Time 0.35
Weight: Cost 0.35
Weight: CO₂ 0.20
Weight: Risk 0.10

Scenario B
Alternative / stress test
Cost band: High (120–250)
Fuel: 92 UAH/L
EF: 2.65 kgCO₂/L
Edge-first: ●
Weight: Time 0.25
Weight: Cost 0.45
Weight: CO₂ 0.20
Weight: Risk 0.10

Actions
Compare, export, brief

KPIs (Δ from A → B)
Negative values are improvements
Cost ↗ 12.4%
Time ↘ 1.2%
CO₂e ↗ 0.0%
Utility ↘ 4.1%

Scenario Comparison
Totals for the selected week and scope

Weight Profiles
Routing preference surfaces

Weekly Plan
Jobs, distance, notes

Day	Jobs	Km
Mon	9	180
Tue	11	210
Wed	8	160
Thu	10	220
Fri	7	175
Sat	5	150
Sun	3	145

Totals: 1240 km • 86 h • fuel≈420 L

Advisories
Auto-generated tips (demo)

Shift heavy routes to early morning to avoid congestion (−4.2% time).

Use Medium cost band with edge-first mode to reduce risk penalties.

Batch irrigations on Tue/Thu windows → −2.8% fuel burn.

Prefer Route B under fuel ≥ 90 UAH/L → −3.1% CO₂e.

Advisories reflect Scenario B preferences vs A under kyiv peri-urban and week 2025-W41.

Fig. 4. Scenario testing delta-KPIs (relative to Scenario A) service demonstration (based on Nazarenko V.'s research data)

while extending those approaches by explicitly considering Ukrainian peri-urban land-use constraints and scenario-specific economic bands.

A particularly important finding is the strong sensitivity of weekly logistics costs to fuel-driven routing conditions, while travel time remained comparatively stable across the tested scenarios. This indicates that, under the current structure of Kyiv's suburban system, within the framework of a controlled scenario experiment, the fuel and cost component is the main source of variation in logistics costs and has a stronger immediate impact on operational planning than the spatial distance itself. Such a result complements previous studies on sustainable routing and green vehicle logistics, which often emphasize carbon and distance optimization, but less frequently examine the role of regional fuel-cost fluctuations and land-use restrictions in shaping route feasibility. The current research, therefore, contributes an applied economic dimension to digital routing studies by showing that the same routing architecture can serve both as a logistics tool and as an instrument for understanding the territorial cost structure of agriculture near large metropolitan areas.

At the same time, the study also reveals several limitations that define the direction for future work. First, the stability of CO_2e values across scenarios indicates that, in the present pilot configuration, emissions are largely driven by uniform distance and fuel assumptions rather than by differentiated low-carbon corridors or machinery classes. Second, the scenario design was intentionally controlled and does not yet represent the full seasonal variability of crop calendars, labor allocation, or weather shocks. Third, while the software interface confirms practical applicability, broader validation with cooperatives, municipalities, and agricultural service providers is still required. Nevertheless, these limitations do not weaken the study's contribution; rather, they confirm that the presented platform should be understood as a scalable middleware-based foundation for further integration of digital twins, real-time mobility feeds, and policy-oriented sustainability accounting.

References

1. Agrawal, J., & Arafat, M. Y. (2024). Transforming farming: A review of AI-powered UAV technologies in precision agriculture. Drones, 8(11), Article 664. https://doi.org/10.3390/drones8110664
2. Aich, S., Chakraborty, S., Lee, Y.-K., & Kim, H.-C. (2022). Digital twins in agriculture: A state-of-the-art review. ICT Express, 8(3), 300–312. https://doi.org/10.1016/j.icte.2021.11.006
3. Arz von Straussenburg, S., Aldenhoff, T., & Riehle, D. (2024). Improving OGC SensorThings API for industrial IoT use cases: Lessons from real-world scenarios. In Proceedings of the 27th AGILE Conference on Geographic Information Science. CEUR-WS. http://ceur-ws.org/Vol-3849/forum1.pdf
4. Awais, M., Wang, X., Hussain, S., Aziz, F., & Mahmood, M. Q. (2025). Advancing precision agriculture through digital twins and smart farming technologies: A review. AgriEngineering, 7(5), Article 137. https://doi.org/10.3390/agriengineering7050137
5. Banerjee, S., Mukherjee, A., & Kamboj, S. (2025). Precision agriculture revolution: Integrating digital twins and advanced crop recommendation for optimal yield [Preprint]. arXiv. https://arxiv.org/abs/2502.04054
6. Falcão, L., Matar, S., Rauch, E., Elberzhager, F., & Koch, K. (2023). Next-generation

interoperability: A framework for data spaces and OPC UA-based automations. Information, 14(8), Article 440. https://doi.org/10.3390/info14080440

7. Guebsi, R., Mami, S., & Chokmani, K. (2024). Drones in precision agriculture: A comprehensive review of applications, technologies, and challenges. Drones, 8(11), Article 686. https://doi.org/10.3390/drones8110686
8. Lin, C., Choy, K. L., Ho, G. T. S., Chung, S. H., & Lam, H. Y. (2020). Green vehicle routing problem: A state-of-the-art review. International Journal of Production Economics, 228, Article 107749. https://doi.org/10.1016/j.ijpe.2020.107749
9. Liu, J., Zhang, D., Li, X., & Wang, L. (2024). Distribution path optimization of carbon emission-reducing agricultural cold chain logistics based on improved GA. Cleaner Logistics and Supply Chain, 12, Article 100164. https://doi.org/10.1016/j.clscn.2024.100164
10. Miller, T., Mikiciuk, G., Durlik, I., Mikiciuk, M., Łobodzińska, A., & Śnieg, M. (2025). The IoT and AI in agriculture: The time is now—A systematic review of smart sensing technologies. Sensors, 25(12), Article 3583. https://doi.org/10.3390/s25123583
11. Nazarenko, V., & Martyn, A. (2025). Urban growth and agrarian dynamics: Evaluating the Kyiv agglomeration’s economic landscape. *Economics and Business Management,* 2(16), 24–41. https://doi.org/10.31548/economics/2.2025.24
12. Nazarenko, V., & Ostroushko, B. (2024). Smart city management system leveraging microservices and IoT. *Energiya*, 1(71), 29–38. https://doi.org/10.31548/energiya1(71).2024.029
13. Obayi, R., Choudhary, S., Nayak, R., & Ramanjaneyulu, G. V. (2025). Pragmatic interoperability for human–machine value creation in agri-food supply chains. Information Systems Frontiers. Advance online publication. https://doi.org/10.1007/s10796-024-10567-x
14. Qiao, Y., Ren, P., Tang, H., & Li, Z. (2023). An interoperable and service-oriented approach for real-time environmental modeling by coupling OGC WPS and SensorThings API. Environmental Modelling & Software, 162, Article 105651. https://doi.org/10.1016/j.envsoft.2023.105651
15. Roccatello, E., Pagano, A., Levorato, N., & Rumor, M. (2025). State of the art in Internet of Things standards and protocols for precision agriculture with an approach to semantic interoperability. *Network,* 5(2), Article 14. https://doi.org/10.3390/network5020014
16. Urdu, D., Berre, A. J., Sundmaeker, H., Rilling, S., Roussaki, I., Marguglio, A., & Wolfert, S. (2024). Aligning interoperability architectures for digital agri-food platforms. Computers and Electronics in Agriculture, 224, Article 109194. https://doi.org/10.1016/j.compag.2024.109194
17. Yousaf, H., Kayvanfar, V., Mazzoni, S., & Elomri, A. (2023). From decision support to Agriculture 4.0: A systematic review of data-driven systems and adoption challenges. Frontiers in Sustainable Food Systems, 7, Article 1107026. https://doi.org/10.3389/fsufs.2023.1107026
18. Zhai, Z., Martínez, J. F., Beltran, V., & Martínez, N. L. (2020). Decision support systems for Agriculture 4.0: Survey and challenges. Computers and Electronics in Agriculture, 170, Article 105256. https://doi.org/10.1016/j.compag.2020.105256

Назаренко В.А.

ПРОСТОРОВО-ЧАСОВА МОДЕЛЬ ВАГОВОЇ МАРШРУТИЗАЦІЇ ДЛЯ ПІДТРИМКИ ЕКОНОМІЧНОГО ПЛАНУВАННЯ СІЛЬСЬКОГОСПОДАРСЬКОГО ЗЕМЛЕКОРИСТУВАННЯ У ПРИМІСЬКІЙ ЗОНІ КИЇВСЬКОЇ АГЛОМЕРАЦІЇ

ЗЕМЛЕУСТРІЙ, КАДАСТР І МОНІТОРИНГ ЗЕМЕЛЬ 2'26: 72-88
http://dx.doi.org/10.31548/zemleustriy2025.02.05

Анотація. *Аграрний сектор України стикається з комплексним економічним і просторовим тиском: змінами у передміському землекористуванні, ускладненою та порушеною логістикою, нестабільними цінами на паливо та обмеженою мобільністю в умовах воєнного стану. Ці виклики особливо помітні в Київській агломерації, де аграрне виробництво дедалі більше залежить від швидкого перепланування в умовах змінних обмежень. У цьому дослідженні представлена та оцінена платформа маршрутизації на основі коефіцієнтів для цифрового аграрного виробництва в Україні, інтегрована в архітектуру проміжного програмного забезпечення, узгоджена з FAIR/OGC, яка консолідує потоки даних отримані із великої кількості джерел (супутникові ЕО, зображення БПЛА за дозволом, телеметрія IoT, завантаженість доріг і затори, а також адміністративно-економічні реєстри тощо). Платформа функціонує як інструмент безперервної підтримки прийняття рішень. Вона дозволяє користувачам гнучко налаштовувати маршрути за чотирма критеріями (час, прямі витрати, викиди* CO_2*е та операційні ризики), тоді як алгоритм автоматично враховує просторові та безпекові обмеження за допомогою жорстких заборонених зон та змінних коефіцієнтів для правильного налаштування модуля обробки даних.*

Проведено імітаційне сценарне моделювання роботи алгоритму відбувалося на основі часових даних чотирьох тижнів у приміській зоні Києва з використанням контрольованого сценарію з трьома тижневими шаблонами: базовим (A), стресовим (B): високі ціни на паливо та вищий транспортний ризик) та скоригованим на сталий розвиток (C). Проміжне програмне забезпечення (ПЗ) підтримувало безперервне генерування рекомендацій під час періодичної доступності БПЛА та короткочасної недоступності мережі, застосовуючи перевірку заповнення баз даних та пересилання, асинхронне оновлення та опрацювання часових рядів даних; експортовані повідомлення про маршрути можна було відтворити як CSV/GeoJSON з повним походженням. Аналіз змодельованих сценаріїв показав високу залежність логістичних витрат за тиждень від зміни цін на пальне. Зокрема, порівняно з базовим сценарієм A, прямі витрати зросли на 12,44% у сценарії B та на 6,22% у сценарії C. Водночас гнучке налаштування коефіцієнтів дозволило зберегти стабільний час проходження маршрутів (загальний час у дорозі для B і C навіть зменшився на 1,15%). Крім того, система забезпечила високу точність планування (понад 95% завдань виконано у задані часові вікна) та повністю уникнула маршрутизації через заборонені зони завдяки застосуванню жорстких просторових обмежень. Загальні показники CO_2*е фіксувалися стабільними у різних сценаріях за уніфікованих коефіцієнтів викидів, що підкреслює необхідність диференційованих низьковуглецевих діапазонів або баз даних у майбутніх пілотних симуляціях.*

Результати свідчать, що стандартизоване проміжне ПЗ та маршрутизація на основі вагових коефіцієнтів може слугувати практичним інструментом управління просторовими даними та аграрною економікою, поєднуючи просторові обмеження, динаміку витрат та індикатори контролю сталості у межах одного операційного робочого процесу.

Ключові слова: *цифрове сільське господарство, маршрутизація на основі питомих коефіцієнтів, проміжне програмне забезпечення, інтеграція UAV–IoT–супутникового забезпечення, приміські зони Києва, логістичні витрати, зміна використання земель, сумісність FAIR/OGC, підтримка прийняття рішень, метрики сталого розвитку..*