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MODELING SUSTAINABLE SUPPLY CHAINS FOR UKRAINE'S EXPORT-ORIENTED INDUSTRIES

Sergiy Grytsenko, Illia Hallini. "Modeling sustainable supply chains for ukraine's export-oriented industries". *The article highlights the need to implement sustainable supply chains as a strategic direction for the development of Ukraine's export potential. It provides a detailed analysis of modern methodological approaches to designing logistics systems that ensure resilience, adaptability, and long-term viability in unstable geopolitical and economic conditions. Particular attention is paid to integrating ESG (Environmental, Social, and Governance) principles into supply chain architecture. The study focuses on agricultural and food sectors as core export-driven industries, recognizing their vulnerability and pivotal role in national economic security. Through a combination of scenario modeling, digital transformation frameworks, and benchmarking best practices from the EU and OECD countries, the article proposes a roadmap for the transformation of Ukraine's logistics systems. The scientific novelty lies in the development of a hybrid model that combines data-driven logistics and regional sustainability metrics, enabling targeted investment and policy planning. The article aims to initiate a broader discussion on the strategic restructuring of Ukraine's export logistics and to serve as a foundation for future empirical studies and pilot implementations.*

Keywords: sustainability, supply chains, export, logistics modeling, agricultural logistics, digitalization, infrastructure, risks, transformation, competitiveness

Сергій Гриценко, Ілья Галліні. «Моделювання сталих ланцюгів постачання для експортоорієнтованих галузей україни». *У статті підкреслюється необхідність впровадження стійких ланцюгів постачання як стратегічного напрямку розвитку експортного потенціалу*

46-54
v.31 (2025)
https://smart-scm.org

України. Наводиться детальний аналіз сучасних методологічних підходів до проєктування логістичних систем, що забезпечують стійкість, адаптивність та довгострокову життєздатність в умовах нестабільної геополітичної та економічної ситуації. Особлива увага приділяється інтеграції принципів ESG (екологічних, соціальних та управлінських) в архітектуру ланцюгів постачання. Дослідження зосереджується на сільськогосподарському та харчовому секторах як основних галузях, орієнтованих на експорт, визнаючи їх вразливість та ключову роль у національній економічній безпеці. Завдяки поєднанню моделювання сценаріїв, концепцій цифрової трансформації та порівняльного аналізу найкращих практик країн ЄС та ОЕСР, стаття пропонує дорожню карту для трансформації логістичних систем України. Наукова новизна полягає у розробці гібридної моделі, яка поєднує логістику на основі даних та регіональні показники стійкості, що дозволяє здійснювати цільові інвестиції та планувати політику. Стаття має на меті ініціювати ширшу дискусію щодо стратегічної реструктуризації експортної логістики України та слугувати основою для майбутніх емпіричних досліджень та пілотних впроваджень.

Ключові слова: сталість; ланцюги постачання, експорт, логістичне моделювання, аграрна логістика, цифровізація, інфраструктура, ризики, трансформація, конкурентоспроможність.

Intraduction. Current geopolitical and economic conditions pose new challenges for Ukraine, particularly in the field of international trade. The most thorough theoretical and methodological foundations of Ukraine's export-import potential have been studied in works [1, 2]. Article [3] is devoted to the study of theoretical and applied aspects of improving the efficiency of foreign economic activity management of enterprises in modern geopolitical conditions. Works [4, 5] are devoted to the organization of supply chains for export and import goods and costs under import and export contracts. The works [6, 7] are devoted to the study of innovative and technological support for the sustainable development of Ukraine's economy in the context of transport and logistics clusters. The works [8-10] are devoted to the modeling of logistics processes, the value system of the eco-supply chain, and the strategizing of enterprises' activities. Successful integration into the global market requires the modernization of logistics infrastructure and the development of sustainable supply chains. Given the high share of agricultural exports, there is a need to rethink approaches to the planning, functioning, and management of export-oriented logistics systems.

The purpose and objectives of the study. The purpose of the study is to comprehensively justify the feasibility of using innovative methods for modeling sustainable supply chains in export-oriented sectors of Ukraine's economy, taking into account current challenges, digital transformation, and sustainable development requirements. Particular attention is paid to the formation of an integrated logistics strategy that ensures the improvement of the efficiency of the national logistics infrastructure, environmental responsibility, and social orientation.

The main objectives of the study include:

– analyzing the current state of export and logistics chains in Ukraine and identifying their weaknesses; studying global experience in designing sustainable supply chains with a focus on the agro-industrial sector and the food industry;

– developing a conceptual model of a sustainable supply chain focused on sustainability, digital integration, and flexibility;

– selecting and justifying a methodological basis for quantitative modeling of chains using scenario analysis tools, KPIs, and geoanalytics; identifying critical success factors for implementing a sustainable chain model in the real conditions of Ukraine;

– Formulation of practical recommendations for state regulation and

the private sector on the construction of logistics hubs, taking into account international ESG standards and the prospects for European integration.

Main material and results. The work uses a systematic approach to modeling, which involves assessing three components: economic efficiency, environmental feasibility, and social impact. The SCOR, Triple Bottom Line, and Data-Driven Logistics models were studied. The analysis showed that traditional logistics networks in Ukraine are vulnerable to risks and have low flexibility. The use of digital platforms, smart contracts, and IoT solutions is proposed to optimize the interaction of chain participants. Within the framework of scenario modeling, potential transport and logistics hubs (Odesa, Lviv, Dnipro) and areas for investment in transport and IT infrastructure have been identified.

In the current global economy, the sustainable development of logistics systems is a key requirement for the functioning of export-oriented sectors. Modeling sustainable supply chains involves a harmonious combination of economic feasibility, environmental safety [11, p. 26], and social responsibility. The Triple Bottom Line (TBL) concept plays a central role in the formation of such models, as it focuses on three components: "profit – planet – people" [12, p. 45].

Global experience shows that countries with a high level of logistics digitization achieve higher efficiency in supply chain management. In particular, the Netherlands, Germany, and South Korea are actively implementing Big Data, IoT, and blockchain technologies in logistics processes. This reduces costs, increases delivery accuracy, and ensures transparency at all stages of goods movement [13].

The Ukrainian logistics infrastructure is undergoing structural transformation. Data from the State Statistics Service of Ukraine indicate uneven development of logistics routes and critical dependence on road transport [14]. A significant part of export flows (especially agricultural products) passes through the seaports in the south of the country, which makes the chains vulnerable to geopolitical risks.

Figure 1 shows the structure of Ukraine's main export destinations in 2023, where the dominance of agricultural products is clearly evident. This highlights the need to improve agrologistics solutions and introduce innovative transport models.

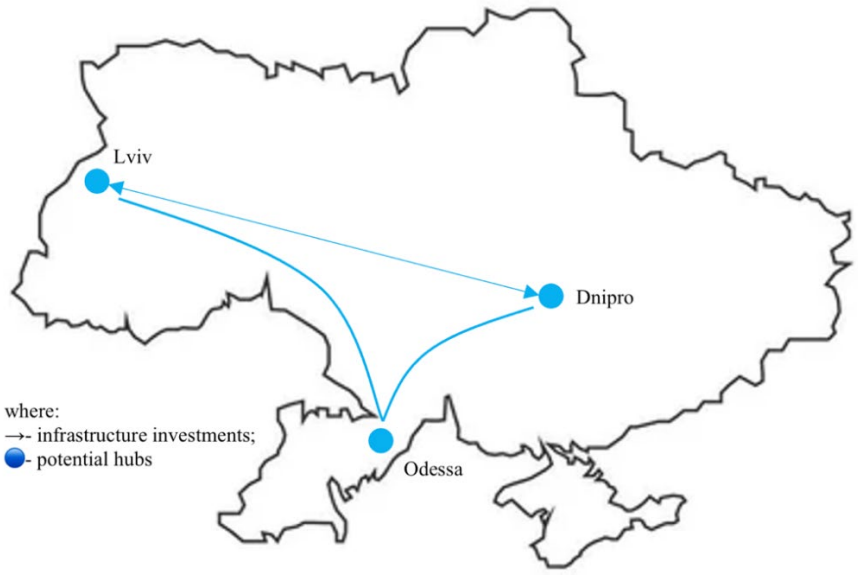

Figure 1 – Logistics hubs and investment areas in Ukraine

The proposed model of a sustainable supply chain (Fig. 2) is based on three subsystems: digital, environmental, and organizational. The digital subsystem covers the use of IoT, automated accounting systems, and smart contracts [15, p. 102]. The environmental component includes the implementation of ISO 14001 standards [16] and carbon footprint calculation. The organizational part involves the construction of flexible logistics networks with a multi-channel supply system.

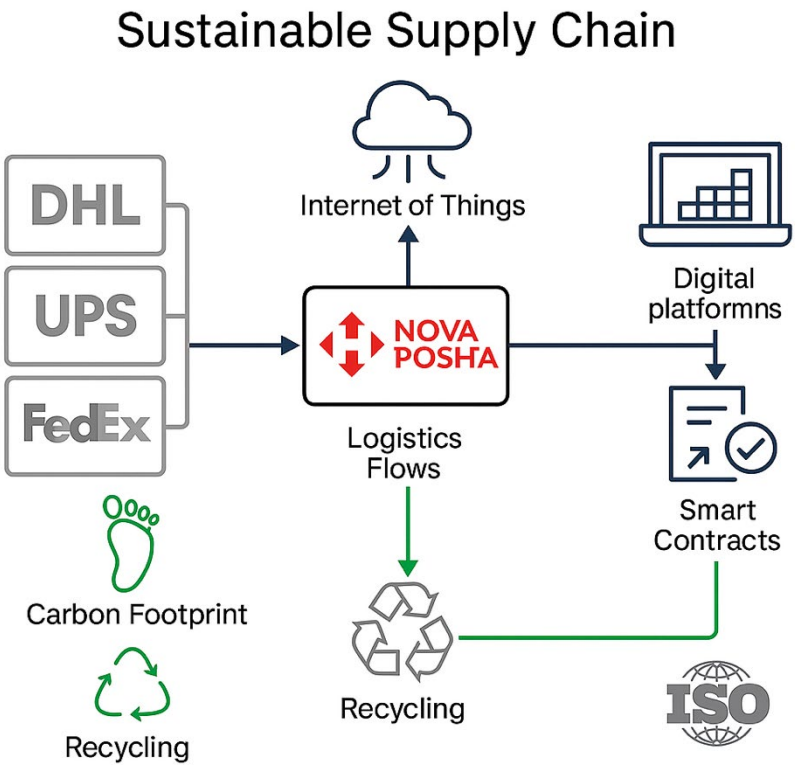

Figure 2 – Model of a sustainable supply chain

Scenario modeling and geoanalytics of logistics hubs. The study included scenario modeling of the development of Ukraine's logistics infrastructure until 2030. Three scenarios were identified: pessimistic (status quo), baseline (integration into the European logistics space), and optimistic (leadership in digital agrologistics in Eastern Europe).

Geoanalytical analysis showed the feasibility of forming transport and logistics hubs in the cities of Odesa, Lviv, and Dnipro, due to their transport accessibility, the presence of cargo redistribution nodes, and proximity to export markets.

Practical recommendations for the public and private sectors. The implementation of a sustainable supply chain model requires the active participation of both public and private institutions. On the part of the state, it is advisable to introduce programs to stimulate investment in logistics infrastructure, digitization of customs procedures, and harmonization with European ESG standards [17]. Particular attention should be paid to creating a legislative framework for the use of smart contracts in foreign economic activity.

The practical implementation of the sustainable supply chain model in Ukraine's export-oriented industries requires coordinated action on the part of the state, business, and the scientific and educational community. A comprehensive cross-sectoral approach focused on the integration of digital solutions, infrastructure upgrades, and

46-54
v.31 (2025)
https://smart-scm.org

adherence to the principles of environmental responsibility is a key factor for success. First and foremost, efforts should be focused on creating a national digital logistics platform that will bring together participants in logistics chains based on modern information technologies. Such a system should ensure transparent interaction between customs authorities, transport operators, exporters, and certification bodies using blockchain, open APIs, and geanalytics tools. This will automate key processes, reduce administrative burdens, and improve control over the movement of goods.

In order to objectively review the existing issues and improve the efficiency of logistics systems focused on foreign markets, it is advisable to propose a project model that provides for the practical implementation of a hybrid concept of a sustainable supply chain adapted to the current conditions of the agro-industrial sector in Ukraine. The project part is based on the use of geoanalytics, KPI analysis, scenario planning, and matrix assessment of sustainability components in logistics systems. As part of the project solution, a tabular structure has been developed for assessing key parameters that form the basis for decision-making in the field of supply chain modernization. Table 1 shows a comparative description of the main challenges and corresponding project solutions adapted to the Ukrainian economic and logistical context.

Table 1 – Analytical matrix of problems and integrated solutions in the context of modeling sustainable supply chains

Identified problem	Area of impact	Proposed solution	Expected effect
High dependence on road transport	Transport logistics	Development of multimodal transport with a focus on rail and water infrastructure	Reduced costs and CO_2 emissions
Fragmentation of the digital infrastructure of logistics operators	Digital logistics	Creation of a national platform for the exchange of logistics data based on open APIs and blockchain technologies	Unification of accounting and reduction of transaction costs
Lack of ESG standards in agricultural logistics practice	Environmental and social sphere	Adaptation of international standards ISO 14001 and GRI to national legislation	Increasing the investment attractiveness of the industry
Low level of logistics education and staff training	Educational and professional sphere	Introduction of interdisciplinary programs and clusters in higher education institutions specializing in logistics	Increasing the competence and innovative potential of employees
Limited access to financing for sustainable logistics initiatives	Financial and economic sphere	Development of green lending mechanisms and subsidies for innovative projects	Activation of the implementation of energy-efficient solutions in logistics

The implementation of these decisions must be supported by the introduction of an effectiveness monitoring system using key performance indicators that allow for the assessment of implementation dynamics and the adjustment of management strategies in real time. It is advisable to use indicators that cover both economic and environmental and social parameters. The metrics presented in Table 2 allow for a balanced approach to

assessing the effectiveness of a sustainable supply chain.

Table 2 –Proposed KPI for assessing the effectiveness of implementing a sustainable supply chain model

Indicator	Unit of Measurement	Target Value for 2030	Data Collection Method
Share of multimodal transportation	%	35–40	Reports from transport operators
Level of logistics process digitalization	%	over 70	Integrated digital logistics IT dashboards
Average carbon footprint	t CO_2/ton-kilometer	-30% compared to 2020 level	ISO 14064, verification systems
Number of environmentally certified warehouses	units	at least 250	Data from the national enterprise register
Share of personnel with relevant training coverage	%	over 80	Surveys, internal company reports

One of the priority areas is the development of multimodal logistics corridors that will ensure the efficient use of rail, road, sea, and river transport. Particular attention should be paid to the modernization of water transport, in particular the restoration of navigation on the Dnieper River, which could significantly reduce transportation costs and greenhouse gas emissions. It is also advisable to stimulate the development of logistics hubs in cities with high transit potential. Achieving environmental goals in logistics is impossible without the use of green financing mechanisms. It is necessary to activate the banking sector in the direction of introducing targeted credit programs for enterprises that invest in the decarbonization of logistics processes, the transition to electric transport, warehouse automation, and the use of renewable energy sources. The introduction of special preferential lending conditions should encourage small and medium-sized businesses to implement eco-strategies.

An important element of the nationwide logistics transformation is Ukraine's active participation in international technical assistance and digital integration programs. Participation in initiatives of the European Union, the World Bank, the EBRD, and other organizations will provide access to advanced technologies, management practices, and financial resources. Such cooperation will contribute to the harmonization of Ukrainian logistics standards with European ESG requirements. Science and education play a special role in shaping the innovative potential of logistics. It is advisable to create interdisciplinary educational and scientific clusters based on specialized universities and research centers [18, 19]. Education, science, and innovation are the drivers of economic modernization in any country and, in general, the drivers of infrastructure development in the context of the fourth industrial revolution. Their task will be to develop applied solutions in the field of digital logistics, scenario modeling, sustainable management, and the formation of a new generation of logistics managers capable of working in a high-tech environment. Prospects for further research in this area cover a number of topical issues, in particular the study of the regional specifics of logistics systems in Ukraine. It is necessary to

model territorially adapted sustainable development strategies, taking into account transport accessibility, existing infrastructure, and the specifics of the export potential of regions. This will avoid uniform solutions and ensure targeted support from the state.

The impact of intelligent technologies on logistics efficiency requires in-depth analysis. The use of artificial intelligence, neural networks, and machine learning opens up new opportunities in demand forecasting, automatic route planning, and real-time adaptation to changes in the external environment. Further research should also focus on the development of ESG metrics that take into account Ukrainian realities and comply with international standards. This will enable businesses to report effectively on their activities and attract investment from global sustainable funds. Practical testing of the hybrid sustainable supply chain model is possible through the implementation of pilot projects in cooperation with logistics operators and export-oriented companies in the agro-industrial complex. The results of such projects can serve as a basis for the formation of a regulatory framework, scaling of decisions, and transformation of Ukraine's logistics policy.

The private sector should invest in the modernization of warehouses, the implementation of ERP systems, and staff training in sustainable logistics management [20, p. 77]. It is necessary to create corporate eco-strategies and ensure reporting in accordance with the principles of sustainable development.

Conclusions. Based on the research conducted, it has been established that modeling sustainable supply chains is not only relevant but also a critically necessary prerequisite for increasing Ukraine's export capacity in conditions of global turbulence. Given the structure of Ukrainian exports, in which more than 40% is accounted for by agricultural and food products, the modernization of logistics systems based on the principles of sustainable development should become a strategic priority both at the level of state policy and in company management. Research has shown that traditional logistics networks, which are mainly focused on road transport, demonstrate low flexibility and high dependence on external threats, in particular geopolitical risks and the vulnerability of port infrastructure. According to the State Statistics Service of Ukraine, about 63% of export shipments in 2023 were carried out by road transport, which creates an additional burden on the carbon balance and reduces the efficiency of supply chains in the long term.

The proposed hybrid model of a sustainable supply chain encompasses three subsystems: digital, environmental, and organizational. The digital component is based on the implementation of IoT technologies, smart contracts, and integrated ERP systems, which will enable more than 70% digital coverage of logistics operations by 2030. The environmental vector of the model involves the introduction of ISO 14001 certification, carbon footprint measurement (with the aim of reducing it by 30%), and the development of green financing for logistics initiatives. The organizational structure of the model is focused on building multimodal routes and creating a new generation of transport and logistics hubs in regional centers – Lviv, Odesa, and Dnipro.

Scenario modeling envisages three possible scenarios for the development of Ukraine's logistics system until 2030, among which the scenario of digital leadership in the Eastern European agrologistics market is considered the most effective. It is expected that, under the conditions of implementation of a comprehensive strategy for sustainable logistics development, the share of multimodal transport will increase from the current 18% to over 40%, the number of certified warehouses will increase to at least 250 units, and more than 80% of logistics personnel will be involved in specialized training. Thus, the sustainable supply chain model is not only theoretically sound but also fully suitable for phased practical

implementation. It ensures the integration of digital technologies, compliance with ESG standards, regional adaptability, and institutional and financial stability. Its implementation will make it possible to form a logistics system capable of responding to crisis challenges, maintaining the continuity of exports, optimizing costs, and at the same time contributing to the fulfillment of Ukraine's international commitments in the field of sustainable development.

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