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MODELING THE IMPACT OF THE LEVEL OF TECHNOLOGICAL DEVELOPMENT ON INTERNATIONAL LOGISTICS PROCESSES IN UKRAINE USING FUZZY LOGIC

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Key words:
fuzzy logic, international logistics, automation, information technology, environmental technologies, transport infrastructure, efficiency of logistics processes.

The article is dedicated to the development of a fuzzy model for assessing the impact of technological development on the efficiency level of international logistics processes. Key factors influencing the efficiency level of international logistics processes are identified: automation level, information technologies, environmental technologies, and transport infrastructure development. The study formulates 60 fuzzy rules that define the relationships between technological variables and the efficiency of logistics processes. The membership functions of the variables are chosen according to their characteristics: trapezoidal, triangular, Gaussian, and sigmoid. The modeling results show that the efficiency level of international logistics processes is at an average level (6.3 out of 10), with automation and digitalization of logistics operations having the greatest impact on its improvement. In addition, it is established that environmental technologies and the development of transport infrastructure also play an important role in increasing logistics efficiency, but their impact is less pronounced compared to digital technologies. A high level of automation combined with environmental innovations will provide an optimal result, emphasizing the importance of not only technological but also environmental development in the field of international logistics. The proposed model can be used for strategic planning and improvement of international logistics processes in the context of digital transformation. Its application allows companies and government bodies to assess the current state of technological development and identify areas for further improvement of logistics activities. The research results can be useful for logistics operators seeking to optimize their processes, increase competitiveness, and reduce the environmental impact of transportation.

МОДЕЛЮВАННЯ ВПЛИВУ РІВНЯ ТЕХНОЛОГІЧНОГО РОЗВИТКУ НА МІЖНАРОДНІ ЛОГІСТИЧНІ ПРОЦЕСИ В УКРАЇНІ З ВИКОРИСТАННЯМ НЕЧІТКОЇ ЛОГІКИ

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Ключові слова:
нечітка логіка, міжнародна логістика, автоматизація, інформаційні технології, екологічні технології, транспортна інфраструктура, ефективність логістичних процесів.

Стаття присвячена розробці нечіткої моделі оцінки впливу технологічного розвитку на рівень ефективності міжнародних логістичних процесів. Визначено ключові фактори, що впливають на рівень ефективності міжнародних логістичних процесів: рівень автоматизації, інформаційні технології, екологічні технології та розвиток транспортної інфраструктури. У межах дослідження сформовано 60 нечітких правил, які визначають взаємозв'язки між технологічними змінними та ефективністю логістичних процесів. Функції приналежності змінних обрано відповідно до їхніх характеристик: трапеціїподібна, трикутна, гаусова та сигмоїдна. Результати моделювання показали, що рівень ефективності міжнародних логістичних процесів знаходиться на середньому рівні (6,3 бала з 10), а найбільший вплив на його підвищення мають автоматизація та цифровізація логістичних операцій. Крім того, встановлено, що екологічні технології та розвиток транспортної інфраструктури також відіграють важливу роль у підвищенні ефективності логістики, проте їхній вплив є менш вираженим порівняно з цифровими технологіями. Високий рівень автоматизації в поєднанні з екологічними інноваціями забезпечить оптимальний результат, що підкреслює важливість не тільки технологічного, а й екологічного розвитку в сфері міжнародної логістики. Запропонована модель може бути використана для стратегічного планування та вдосконалення міжнародних логістичних процесів у контексті цифрової трансформації. Її застосування дозволяє компаніям і державним органам оцінювати поточний стан технологічного розвитку та визначати напрями для подальшого вдосконалення логістичної діяльності. Результати дослідження можуть бути корисними для логістичних операторів, що прагнуть оптимізувати свої процеси, підвищити конкурентоспроможність і знизити екологічний вплив транспортних перевезень.

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Statement of the problem

Modern international logistics is significantly influenced by technological innovations that are transforming traditional supply chains. The introduction of the Internet of Things, blockchain, artificial intelligence, and automation is changing logistics processes, increasing their efficiency, transparency, and adaptability to market changes. However, assessing the real impact of these technologies is complicated by the lack of universal methodologies capable of accounting for uncertainty and subjective factors, such as management quality, the level of digital readiness of a company, or the impact of the external environment. Fuzzy logic allows for the formalization of such vague criteria and provides a quantitative assessment of their impact, making it an ideal tool for analysis in a dynamically changing business environment.

Analysis of recent studies and publications

The relevance and importance of implementing innovative technologies in international logistics is undeniable, which is confirmed by active research on this issue both among scientists studying theoretical aspects and practitioners directly facing the need to optimize logistics processes in various sectors of the economy. In particular, Bokovets V., Davydiuk L., and Pyliavoz T. in their work [1] investigated the introduction of innovative technologies (information, technological, managerial, and environmental, including IoT, AI, blockchain, and automation) in international logistics and their impact on process optimization, cost reduction, and efficiency improvement, and also identified obstacles to their implementation. Shatska Z.Ya. and Stuzhny O.S. [2] determined that logistics is at the sixth stage of development – "logistics of the future," where an integrated flow management system is being formed, actively adapting to new conditions through areas such as Logistics 4.0 and green logistics. Mogilevska O.Yu., Slobodyanyk A.M., and Sidak I.V. [3] proved that artificial intelligence significantly simplifies the processing of large volumes of data and increases productivity, which has a significant impact on the economy, including logistics processes, and contributes to GDP growth and business process optimization. Hrynko I.M. [4] investigated the impact of the latest blockchain technology on the development of international trade between countries, particularly on supply chains, and identified the main obstacles to the implementation of blockchain. Nakonechna T.V. and Gryniv N.T. [5] examined the importance of innovative technologies in logistics, determined their impact on supply chains and enterprise efficiency, and described key modern technologies, their advantages, implementation features, and the effects obtained for participants in the logistics chain. Khmelovsky O.V. [6] considered the features, trends, and challenges of the development of international logistics in the context of globalization, and also characterized the levels of its globalization and the conditions for their achievement. Malashchuk D.V. and Hrynchak N.A. [7] analyzed the current state of the global logistics services market, identified key trends and factors of its differentiation, studied the dynamics of development, and developed a forecast for its further growth. Makedon V.V. [8] investigated the impact of digital technologies on international logistics, developed a model for their integration into logistics processes, and provided recommendations for improving the efficiency of logistics operations.

Objectives of the article

The purpose of the article is to develop a model for assessing the impact of technological development on the efficiency level of international logistics processes in Ukraine using fuzzy logic tools.

The main material of the research

To model the impact of technological development on international logistics processes in Ukraine, the authors believe it is appropriate to use fuzzy logic. Since fuzzy logic allows modeling complex systems where parameters and conditions can be defined imprecisely, within certain ranges, or with fuzzy gradations. In general, the mechanism of logical inference includes four stages: fuzzification, fuzzy inference, composition, and defuzzification. The authors propose an algorithm for modeling the impact of the level of technological development on international logistics processes in Ukraine, presented in Fig. 1.

According to the proposed methodology, the first stage formulates the task, which is to determine the impact of technological development on the efficiency level of international logistics processes (ELP) in Ukraine. The second stage identifies the tuple of input variables and the output variable. Based on the analysis of scientific research, the following factors of technological development are selected:

– automation level (RA), the degree of implementation of automated systems in logistics processes, such as robots, automated warehouses, drones, etc.;

– information technologies (IT), the degree of development and implementation of modern information technologies, such as the Internet of Things (IoT), Big Data, and blockchain, for tracking, managing, and analyzing logistics processes;

– environmental technologies (ET), the implementation of technologies aimed at reducing the environmental impact of logistics processes (e.g., electric trucks, energy-efficient warehouses, reduction of CO2 emissions, etc.);

– development of transport infrastructure (TI), the degree of development of transport infrastructure, including roads, ports, airports, railway networks, etc., and their compliance with the latest technologies.

Thus, the tuple of input linguistic variables of the fuzzy model is: $< RA, IT, ET, TI >$, and the output parameter is the efficiency level of international logistics processes (ELP). At the third stage of constructing the fuzzy model, implemented in the Fuzzy Logic Toolbox of Matlab, the linguistic representation of the variables is defined. The terms of the specified input and output linguistic variables are defined as fuzzy sets [9]:

$$T_i = \left\{\left(x, \mu_{Ti}(x)\right) : x \in X, \mu_{Ti}(x) \in [0, 1]\right\},$$

where $\mu_{Ti}(x)$ – is the membership function of the corresponding fuzzy set.

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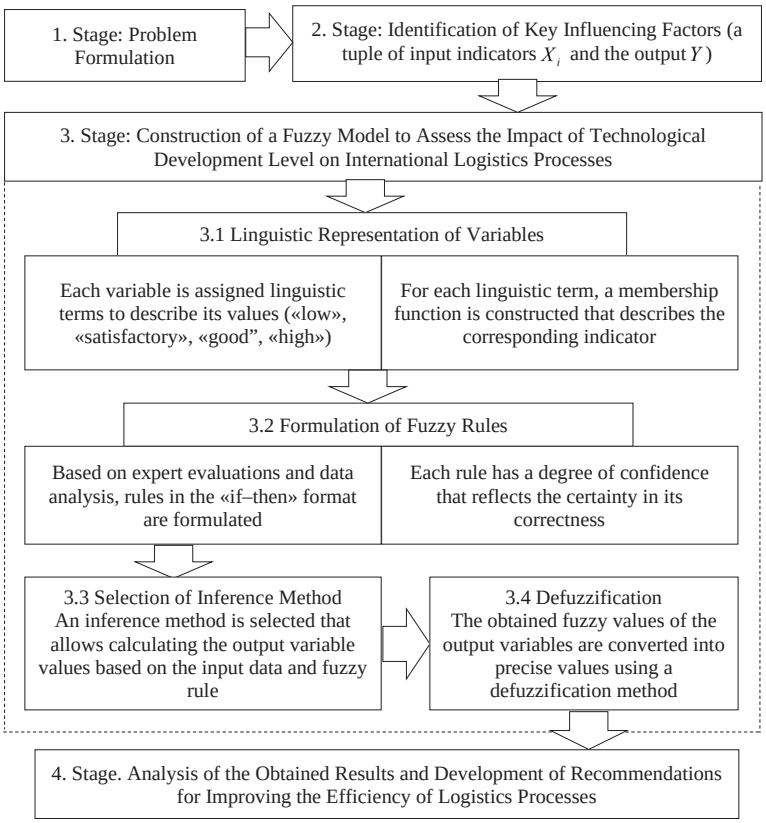

Fig. 1. – Algorithm for modeling the impact of the level of technological development on international logistics processes

Source: developed by the authors

The efficiency level of international logistics processes is studied under conditions of uncertainty, therefore, the following range of term definitions is accepted:

$$RA = \begin{cases} \text{low} \in [0;\ 0{,}25] \\ \text{satisfactory} \in [020;\ 0{,}50] \\ \text{good} \in [0{,}45;\ 0{,}75] \\ \text{high} \in [0{,}70;\ 1] \end{cases} \qquad ET = \begin{cases} \text{low} \in [0;\ 0{,}25] \\ \text{satisfactory} \in [020;\ 0{,}50] \\ \text{good} \in [0{,}45;\ 0{,}75] \\ \text{high} \in [0{,}70;\ 1] \end{cases}$$

$$IT = \begin{cases} \text{low} \in [0;\ 0{,}25] \\ \text{satisfactory} \in [020;\ 0{,}50] \\ \text{good} \in [0{,}45;\ 0{,}75] \\ \text{high} \in [0{,}70;\ 1] \end{cases} \qquad TI = \begin{cases} \text{low} \in [0;\ 0{,}25] \\ \text{satisfactory} \in [020;\ 0{,}50] \\ \text{good} \in [0{,}45;\ 0{,}75] \\ \text{high} \in [0{,}70;\ 1] \end{cases}$$

Output term definition range:

$$ELP = \begin{cases} \text{low} \in [0;\ 0{,}25] \\ \text{satisfactory} \in [020;\ 0{,}50] \\ \text{good} \in [0{,}45;\ 0{,}75] \\ \text{high} \in [0{,}70;\ 1] \end{cases}.$$

If the efficiency level of international logistics processes is low, this indicates serious problems in supply chain management, which can lead to losses and a loss of competitiveness at the international level. Satisfactory – logistics processes can function quite effectively but require improvement to achieve better performance in international trade. Good – logistics processes operate efficiently, ensuring stable and reliable deliveries with minimal costs, which allows for successful competition in the international market. High efficiency means that a company or country has significant advantages in international trade, ensuring fast, reliable, and economical deliveries with minimal environmental impact.

Input terms are evaluated on a 10-point scale, where 0 means no development at all, and 10 means a high level of technology development. The value of the membership function lies in the range from 0 to 1, where 1 is a complete correspondence to the truth of the statement, and 0 is its complete absence.

A trapezoidal membership function is used to describe the variable «Automation Level», which effectively models clearly defined levels (low, satisfactory, good, high) with gradual transitions between them. This function allows for a more accurate representation of intermediate states of automation, which is typical for complex production and logistics systems. The variable «Information Technologies» is described by a triangular membership function, which provides clear intersection points between levels of technology development. A Gaussian membership function is used for the variable «Environmental Technologies». It provides a smooth and continuous transition between levels, which is especially important for processes with gradual but constant changes. The use of this function is justified by the fact that

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environmental technologies usually develop without sharp jumps, and their implementation has a long-term and predictable nature. The development of transport infrastructure is modeled by a sigmoid membership function, which well reflects processes with abrupt changes. In the real world, infrastructural development often goes through periods of rapid growth after reaching a certain critical level. The sigmoid function allows for a correct description of these features, providing a realistic modeling of the transition from a low level to a high level. Fig. 2 shows the membership functions for the input variables.

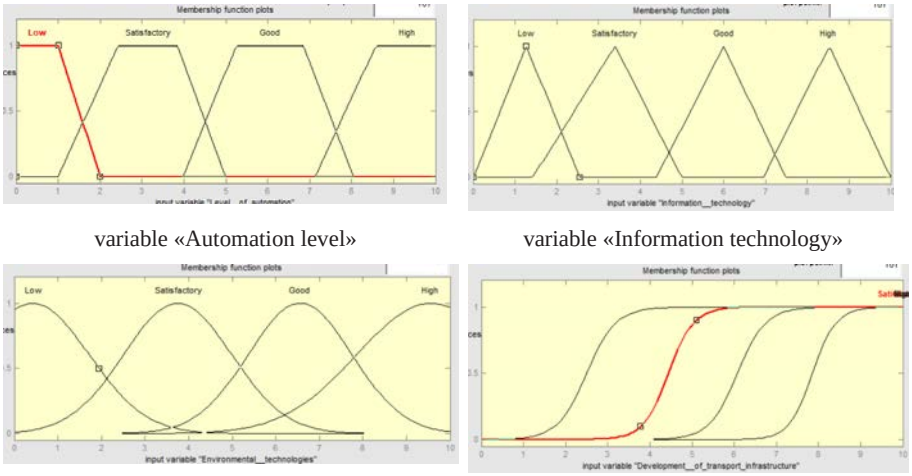
A trapezoidal membership function is used to describe the output variable «Efficiency of International Logistics Processes» (Fig. 3). After all, this type of function makes it possible to well describe situations where efficiency remains at a certain level for some time interval and allows for describing a wide range of efficiency with clearly defined high and low levels. This allows for considering the possibility of a stable high level of efficiency within a certain range and a gradual decrease to lower levels.

The next step of the third stage is to select the inference method; the Mamdani and Sugeno algorithms are most commonly used. The authors chose the Mamdani algorithm because it allows for effective modeling of complex relationships between influencing factors, takes into account expert assessments, and provides an intuitively understandable output result in the form of fuzzy assessments of the impact level of technological development on international logistics. The Sugeno algorithm is more suitable for accurate forecasting when it is necessary to obtain a numerical value, for example, for optimizing logistics costs.

The Mamdani fuzzy inference algorithm is based on the formation of a rule base of the following type [9, 10]:

$$IF\left(x_1\ IS\ X_1^{(i)}\ AND\ x_2\ IS\ X_2^{(i)}\ AND\ \ldots\ AND\ x_n\ IS\ X_n^{(i)}\right)$$
$$THEN\ I_{ELP} = Y_k^{(i)},\ i = 1,\ldots,\ I,$$

where $X_1^{(i)}, X_2^{(i)}, \ldots, X_n^{(i)}, Y_k^{(i)}$ – are the values from the term set corresponding to the *-i* rule.



variable «Automation level» | variable «Information technology»

variable «Environmental technologies» | variable «Development of transport infrastructure»

Fig. 2. – Membership functions of the model's linguistic variables

Source: developed by the authors

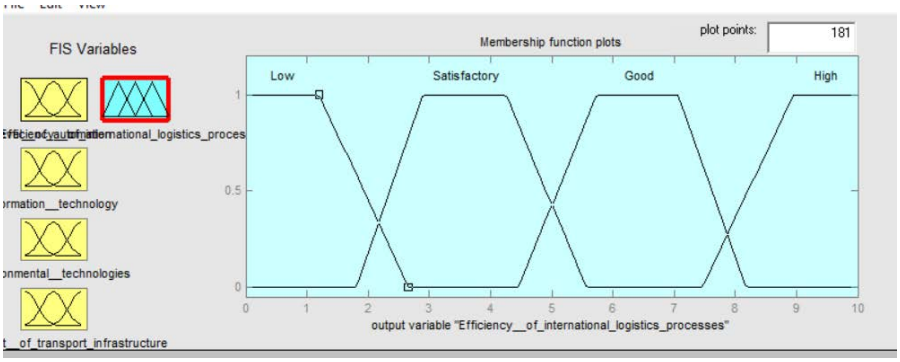


Fig. 3. – Trapezoidal membership function of the variable «Efficiency of International Logistics Processes»

Source: developed by the authors

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At the next step of the third stage, defuzzification of the fuzzy sets of the output variables is performed. Defuzzification according to the Mamdani algorithm is determined by the centroid method, which consists of finding the average value in the area under the graph of the membership function. This is the most commonly used method, where the defuzzification result is determined as the center of mass for the graph of the membership function [11]:

$$y_k = \frac{\int_{\min}^{\max} y \cdot \mu_k(Y_k)\, dy}{\int_{\min}^{\max} \mu_k(Y_k)\, dy},$$

where y_k – is the defuzzified value of the k-th fuzzy set of the output variable; $\mu_k(Y_k)$ – is the membership function of the fuzzy set of the output variable Y_k, I_{ELP} are the boundaries of the universe of the variable I_{us}.

Then, the impact of technological development on the efficiency level of international logistics processes according to the Mamdani fuzzy inference algorithm is determined by the formula:

$$I_{ELP} = \frac{\sum_{k=1}^{m} y_k \mu_k(Y_k)}{\sum_{k=1}^{m} \mu_k(Y_k)},$$

where m is the number of fuzzy sets (elements of the term set) of the output variable I_{ELP}.

Considering the number of variables and possible terms, 60 fuzzy rules were formed, based on expert assessments in this field. Each rule considers different combinations of input variables (RA, IT, ET, TI) and determines the corresponding efficiency level. The formed rules provide an understanding of the relationships between different technological factors and their impact on the efficiency of international logistics processes.

In the process of defuzzification, which involves converting fuzzy results obtained based on the rules into a specific numerical value, an assessment of the impact of technological development on the efficiency of international logistics processes in Ukraine was carried out. Assessing the level of development of automation, information technologies, environmental technologies, and the development of transport infrastructure in Ukraine is a complex task, as these indicators vary depending on the industry, region, and other factors:

– the level of automation is satisfactory, as the level of automation in industry and manufacturing in Ukraine is growing, but it remains at an average level compared to developed countries. There are sectors, especially in large cities and modern enterprises, where automation is well developed, but many enterprises still use old technologies;

– the development of information technology is at a high level. The IT sector in Ukraine is developing rapidly and is one of the strongest in the economy. Ukraine is known as a center for software outsourcing and has a developed IT infrastructure, which contributes to a high level of IT integration into business processes. The IT sector is one of the strengths of the Ukrainian economy;

– the level of environmental friendliness of technologies is low, but closer to average (satisfactory). The adoption of environmental technologies in Ukraine is only gaining momentum. Although there are initiatives and individual projects, the overall level of use of environmentally friendly technologies and standards remains low to medium. More and more attention is being paid to this topic, but significant improvements are still needed;

– the development of transport infrastructure is satisfactory. Ukraine's transportation infrastructure is not uniformly developed. Large cities have relatively well-developed infrastructure, but the overall condition of roads, railways, airports, and ports often requires modernization. Despite some progress, there are still many infrastructure problems, especially in rural and remote areas. Given the current situation in the country and the damage that Russia is doing to Ukraine's infrastructure, infrastructure development requires significant investment and modernization to reach a higher level.

The results of the fuzzy model implementation are shown in Fig. 4.

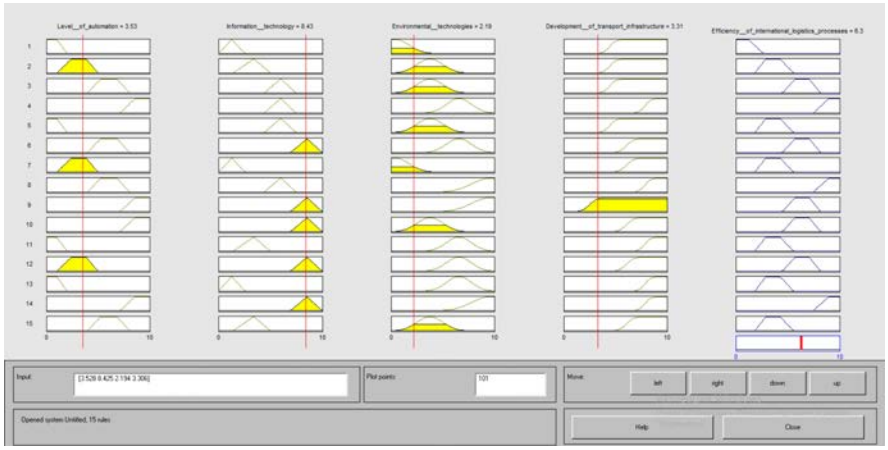

Fig. 4. – Results of implementing a fuzzy model for assessing the impact of technological development on the efficiency of international logistics processes in Ukraine

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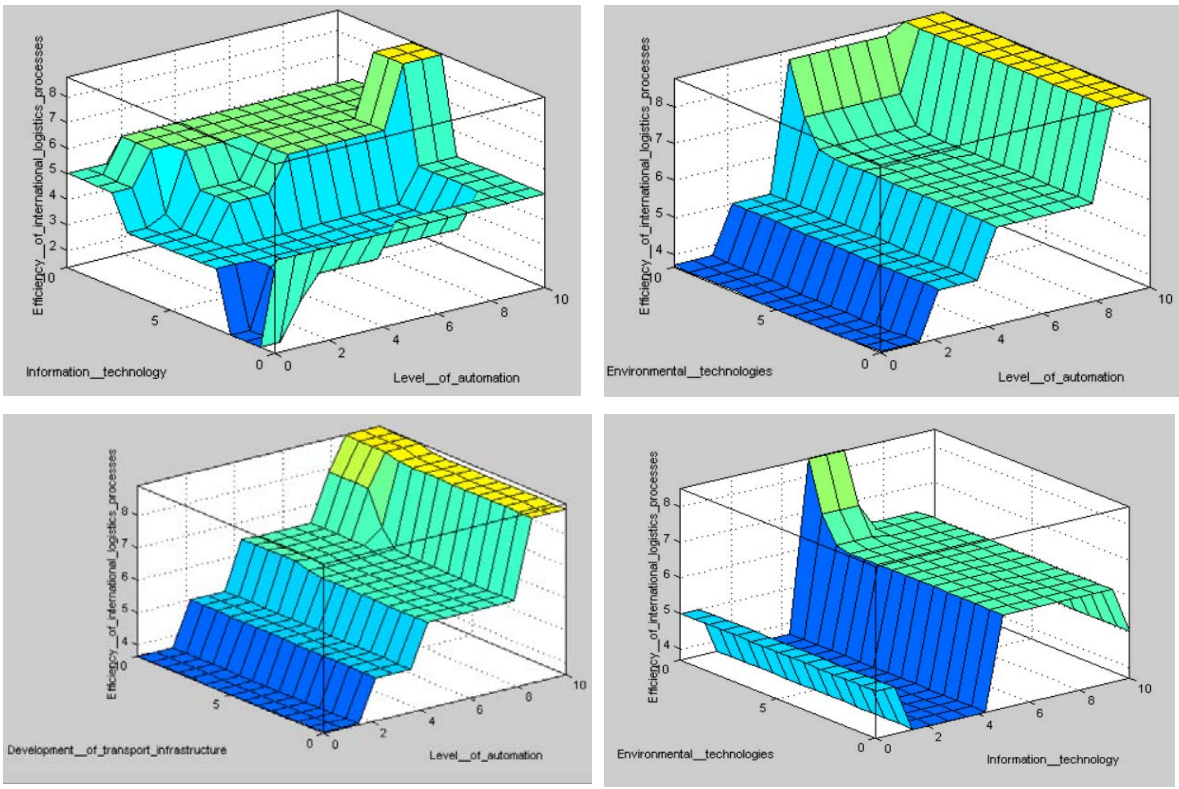

Fig. 5. – Surface of fuzzy inference of the level of efficiency of international logistics processes
Source: built by the authors

At the fourth stage of the proposed algorithm (Fig. 1), we analyzed the results and found that the level of efficiency of international logistics processes is 6.3 points on a 10-point scale, indicating an average level of development of the industry. This indicates that key technological factors such as automation, use of information technology, implementation of environmental solutions, and development of transport infrastructure have a significant positive impact, but their potential is not fully realized. To achieve a higher level of efficiency, it is necessary to focus on further integration of innovative technologies, process optimization, and environmental sustainability, as well as on improving the infrastructure that supports the international circulation of goods. Such measures will not only improve the quality and speed of logistics operations but also reduce their cost, which will help strengthen international competitiveness.

A visual representation of the impact of technological development on the level of efficiency of international logistics processes is shown in Fig. 5.

Analyzing the results presented in Fig. 5, we can conclude that the efficiency of international logistics processes largely depends on the level of automation and the introduction of information technology. High values of these factors contribute to maximum efficiency, while low values of automation and information technology lead to a significant decrease in efficiency. This emphasizes the need for a comprehensive approach to the introduction of technology into logistics processes, where the lack of development in both areas significantly limits efficiency. To maximize efficiency, it is important to integrate automation with environmental technologies. Their interaction yields significantly better results than the separate implementation of each factor. A high level of automation combined with environmental innovations provides an optimal result, which emphasizes the importance of not only technological but also environmental development in the field of international logistics. The analysis of Fig. 5 confirms that the efficiency of international logistics processes also largely depends on the development of transport infrastructure. The best way to achieve the maximum level of efficiency is to simultaneously improve both technological solutions and infrastructure. The gradual improvement of each factor allows for consistently high efficiency, but at certain stages of development, saturation may occur, which indicates the need for a comprehensive approach to investment in all aspects of the logistics system.

Conclusions

The results of the study showed that a high level of automation and information technology contributes to efficiency growth, while insufficient development of these factors limits the possibilities for increasing productivity. The analysis of the situation in Ukraine showed an average level of technology development in logistics, in particular, the level of automation and environmental technologies requires significant improvements, while information technology and the development of transport infrastructure are at a satisfactory level. In order to achieve a higher level of efficiency in international logistics processes, it is necessary to focus on further development of automation,

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integration of modern information technologies, introduction of environmental technologies, and improvement of transport infrastructure. An integrated approach to the development of technological and infrastructure components will help reduce costs, increase competitiveness, and strengthen positions in the international market.

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