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Towards Green Industrial Development in Ukraine: A Decision Model for Post-Industrial Production Strategies

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Abstract
The issue of modelling decision-making in the field of green production in a post-industrial society determines the relevance of the study. The main goal of the study is to develop a decision-making model that can help green industry organizations identify optimal strategies and actions to reduce environmental impacts, ensure sustainable efficiency, and promote development. The methodology used in the study involved a theoretical analysis, synthesis, and mathematical modelling methods. As a result, an innovative mathematical model was developed and proposed, which allows predicting the influence of various factors when choosing the optimal production strategy. The results show that the application of the developed model allows Ukrainian enterprises in the field of green production to determine optimal strategies aimed at reducing the environmental impact of production processes on the environment. It helps to ensure sustainable production efficiency, contributing to the economic sustainability of enterprises and the global economy.

Keywords
Optimisation, environmental efficiency, strategic management, sustainable development, environmental conservation.

Introduction

The modern world is undergoing a transition to a post-industrial society, where sustainable development has become a priority for all of humanity, and business in particular. Green production is one of the most important areas requiring focused study and problem solving. In a general sense, green production is defined as an economic activity aimed at producing goods and services with the least possible negative impact on the natural environment and society (Zameer et al., 2020). In recent years, green production has become an increasingly important aspect of the development of enterprises and states. This increases the relevance of updating and modernizing production strategies in accordance with the requirements that have arisen, which leads to the need for an in-depth investigation and analysis of the issue. Thus, the relevance of the chosen topic lies in the fact that green production in a post-industrial society is a necessity for preserving the natural environment, ensuring the sustainability of the economy and improving the quality of life of society.

Although the fundamentals of green production are widely known, there is still a lack of tools and frameworks for modelling decision-making processes in a way that balances social, economic, and environmental aspects of production in a post-industrial setting. Current models typically lack a complete approach, instead concentrating narrowly on either the economic costs or the environmental implications. By creating a novel mathematical model that incorporates the environment, economy, and social considerations – the three pillars of sustainability – this study seeks to close that gap and provide guidance for the best decision-making techniques for environmentally friendly production manufacturing.

Green production includes many aspects, such as optimizing resources, reducing emissions and costs, ensuring safe working conditions, increasing competitiveness, and complying with environmental regulations (Leonard et al., 2021). American researcher Li (2020) defines green infrastructure as a system of natural and artificial elements that include environmental, eco-

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nomic, and social functions. Enhancing one's physical and mental well-being as well as encouraging social participation and community involvement are its social functions. The economic function involves lowering health care costs and flooding while raising investment, rent, and property prices. It also helps the green economy. In terms of environmental function, it entails flooding problems, air pollution reduction, stormwater contamination, and the restoration of green space in industrial regions. The researcher claims that green production is impossible without establishing a green infrastructure that helps post-industrial cities in the transition to sustainable development. Ivanyuta & Yakushenko (2022) note that Europe aims to achieve climate-neutral indicators by 2050. The main objective of the European Green Deal (EGD) is to develop renewable energy sources, and improve the energy efficiency of production facilities and other measures aimed at reducing greenhouse gas emissions (European Commission, 2019).

However, in a post-industrial society, green production faces numerous challenges that require comprehensive strategies and innovations to achieve the sustainability and environmental suitability of production. The main challenges include: limited natural resources, the risk of environmental pollution, climate change, political and legal pressure, and increasing consumer awareness (Leonard et al., 2021; Takovski, 2020). In general, in the modern world, more and more countries are introducing legal regulation of the manufacturing industry, considering "green" trends and in order to improve the environmental situation and minimize the negative impact of production on the environment. Thus, the Ukrainian researcher Markevych (2020) argues that the "green" trend is one of the most important trends of our time. It is associated with the transition to sustainable development, which involves minimizing the negative impact of human activities on the environment. Within the framework of the European Union (EU), this movement is implemented on the basis of the European Green Deal, which provides for achieving a carbon-neutral economy by 2050.

Regulatory framework for the manufacturing industry is relevant for many countries around the world. The study by Kolcava et al. (2020) distinguishes two main modes of environmental regulation of the production industry: the mode of directives and the mode of market instruments. These instruments include emissions trading systems, pollution taxes, subsidies for environmentally friendly practices, and green certifications. In contrast to conventional command-and-control laws, market mechanisms offer financial incentives to companies that internalize environmental costs and cut pollution or implement sustainable practices (Sutbayeva et al., 2021). The authors note that it is the directive regime that is the most common regime of environmental regulation in post-industrial societies. This is because such a regime is more effective for achieving specific environmental policy goals. The directives set specific goals and obligations for businesses, allowing the government to monitor progress towards these goals.

Considering the Ukrainian policy in the field of green production, it is necessary to highlight a number of regulatory documents: Law of Ukraine No. 1818-IX "On Energy Efficiency" (2023), Decree of the President of Ukraine No. 722–2019 "On the Sustainable Development Goals of Ukraine for the period up to 2030" (2019), and Law of Ukraine No. 555–IV "On Alternative Energy Sources" (2023). These laws and regulations provide for such measures to support green production in Ukraine as the introduction of environmental standards and requirements for production, stimulating the use of resource-saving technologies, developing renewable energy sources, and creating conditions for the development of the processing industry. However, despite this, there are still some difficulties in Ukraine regarding the compliance of production processes with "green" requirements. Markevych (2020) attributes the insufficient investment, low level of economic development of the country, and political instability to the main problems of Ukrainian green production.

Ukrainian researcher Ohanisyan (2022) highlights the need to introduce "green" initiatives in the field of agricultural production. The researcher argues that the agricultural sector should move to the principles of sustainable development, in order to respond to current challenges (climate change, the growing needs of humanity for food, the problem of environmental pollution). As part of research, Bilovytska (2022) analyses the mechanisms of cooperation between the state and business in the context of sustainable development of the "green" economy in Ukraine, in particular highlighting the forms of public-private partnership and emphasizing the need to improve these mechanisms in order to achieve successful implementation of the sustainable development policy.

The main task of modern enterprises is to find the optimal decision-making strategy in the field of green production, with the condition of achieving a balance between the environmental, economic and social aspects of their activities (Anarbayev et al., 2023). The solution to this problem requires the development of tools and methods that will help consider various criteria and constraints in the decision-making process. In general, most of the research is aimed at determining the principles of green production and the impact of "green" trends on the development of various industries,

studying regulatory regulation. However, the available research does not reveal the impact of green production on the economy of enterprises and management decision-making processes.

Thus, the goal of the current research is to develop an optimal tool for modelling the decision-making process in the area of green manufacturing in a post-industrial society. Given the definition of the main problematic aspects and topical issues, and considering the main goal, the research objectives include the following:

1. Definition of the key principles and challenges of implementing green production practices.
2. Analysis of barriers and challenges facing the introduction of green production in the Ukrainian manufacturing sector, including the agricultural, industrial, and energy segments.
3. Formalizing a multi-criteria decision model that integrates environmental, economic, and social indicators to evaluate the impacts of different production strategies.
4. Demonstrating the model's applications through analysis of decision-making for green production in the context of Ukraine's unique challenges and post-industrial transition.

Materials & Methods

A theoretical study was conducted aimed at developing an optimal tool for modelling the decision-making process in the field of green production within a post-industrial society. The study was conducted directly on the basis of available scientific literature, statistical and regulatory information, as well as an analysis of the structure and characteristics of the industry. The materials used contain papers, monographs, conference reports, and other sources from the field of green production, sustainable development, and decision-making. The main emphasis was placed on papers containing theoretical and methodological approaches to the analysis of topical issues. All information used is freely available on the Internet.

Analysis and synthesis methods were used to study in detail the interaction of various factors in the field of green production and their impact on decision-making. The analytical tools allowed us to conduct a detailed review of various factors and main trends, and identify the advantages and disadvantages of current decision-making models in terms of sustainability, environmental impact, cost of mechanisms and resource optimization. The synthesis was used to conduct a comprehensive review and study of various factors that affect the decision-making process in the field of green production. This method allowed combining various aspects of the study and assessing their impact on the decision-making process, creating a more detailed and comprehensive picture of the situation.

According to this, a mathematical model of decision-making in the field of green production was developed. The proposed model is based on the use of various indicators obtained as a result of data analysis and synthesis and allows evaluating the effectiveness of various possible decision-making options, considering various factors of influence. The mathematical modelling methods in this study played a key role in the development and analysis of a theoretical model of decision-making in the field of green production in a post-industrial society. The main stages of using mathematical methods included the following: formalization of the problem, determination of parameters, development of a mathematical model, and analysis of the sensitivity and flexibility of the model to changes in parameters and constraints.

The proposed model considers economic, environmental, and social aspects, allowing the study to assess the impact of various strategies on these criteria, and has the following form:

$$F(X) = k_1 \cdot E(X) + k_2 \cdot C(X) + k_3 \cdot S(X), \quad (1)$$

where: $F(X)$ – a goal function that calculates the total effect of the selected vector of the production strategy, where each component X_i corresponds to the volume of production for an individual product or service; k_1, k_2 and k_3 – weighting factors reflecting the importance of each impact factor; E – vector of environmental indicators reflecting the environmental impact of each strategy option (calculated as the compliance of the existing compliance indicator with the reference indicator (≤ 1)); C – vector of production costs, reflecting the production costs of each product or service; S – vector of social indicators, reflecting the social impact of each strategy (calculated as the compliance of the existing compliance indicator with the reference indicator (≤ 1)). At the same time, the value of $F(X)$ should tend to the minimum permissible (desired) indicators, if a result is obtained where $F(X) > F_{\min}$ – the strategy is considered suboptimal and needs to be revised.

The method of mathematical modelling acted as an important tool for research and optimization of decision-making in the field of green production. The chosen methodology facilitated a systematic study of various aspects of this problem and provided an opportunity to gain a full understanding of the issue and propose a decision-making model for the optimal

production strategy, considering the complex impact on sustainability, efficiency, and environmental sustainability of production.

Results and Discussion

Basic principles of green production

Green production is an approach to production aimed at achieving sustainable development and reducing the negative impact of industry on the environment (Cui & Wang, 2021). One of the main principles of green production is to minimize emissions and pollution, including reducing harmful emissions into the atmosphere, controlling water pollution, and preserving soil. This principle implies the use of clean technologies and efficient waste management methods. In addition, green production is aimed at the rational use of natural resources, in particular energy and raw materials, which is made possible by the use of renewable energy sources, reducing losses during the transportation, recycling, and reuse of materials. It is also important to note that green production involves creating products that are safe for consumers and the environment (Yousaf, 2021). Thus, manufacturing enterprises and the state should monitor the content of harmful substances in products, and the development and application of environmentally friendly materials and technologies. According to this, green production requires the introduction of management systems that allow monitoring and reducing the negative impact of production on the environment, and improving the productivity and quality of enterprises' activities.

In general, green production is an important incentive for the development of research and innovation in the field of sustainable production. This principle contributes to creating a comfortable environment for the development and implementation of new technologies, approaches, and products that are aimed at reducing the environmental impact of production and improving it. For example, renewable energy technologies like solar photovoltaics, wind turbines, geothermal systems can reduce reliance on fossil fuels. Environmental consequences can be better tracked and optimized with the use of environmental monitoring technology such as satellite monitoring, artificial intelligence/machine learning models, and sensors. Products have a smaller environmental impact thanks to advancements in sustainable materials including bio-based polymers, green concrete, and recyclable materials. Clean production technologies use cleaner inputs, recycling systems, and process improvements to reduce waste, emissions, and effluents during manufacturing.

Research in the field of green production covers a wide range of topics, including the development of renewable energy sources, the creation of more efficient resource management technologies, improving waste management methods, and the development of environmentally friendly materials. Researchers are working to integrate these solutions into enterprise production processes to reduce emissions and optimize resource-intensive processes. Those enterprises that implement innovative solutions in the field of green production gain a competitive advantage in the market (Yatsiv & Cherevko, 2022). New technologies can reduce energy and resource costs, reduce waste treatment costs, improve product quality, and meet consumer requirements for the environmental suitability of products (Awan et al. 2021). Innovation in green production also contributes to the creation of new markets and the development of a sustainable economy, which is an important step towards achieving sustainable development in a post-industrial society (Madiyarova et al., 2019).

Green production, in addition to caring for the natural environment, also considers social aspects, covering the processes of creating safe and comfortable working conditions for workers in production (Woo & Kim, 2019). By helping to improve working conditions, green production aims to provide physical and psychological comfort for workers, which can have a positive impact on their productivity and health. Green production also emphasizes relationships with the communities in which production operates. It seeks to take into account the views and needs of local communities, promoting partnership and cooperation. This is important to ensure that green production projects are adopted at the community level and receive support from local residents.

The final principle of green production is to promote cooperation and information exchange between countries to achieve common sustainable development goals. For instance, nations can exchange case studies, best practices, and lessons discovered in converting important sectors of the economy, such as manufacturing, energy, and transportation, to more environmentally friendly modes of operation through green production methods. Technologies may be transferred between nations for mutual gain as they share specialists, information, and intellectual property related to groundbreaking advancements in green production. Openness and group responsibility for achieving sustainable objectives can be guaranteed by data sharing and cooperative monitoring of environmental indicators like emissions levels. Such a global approach helps to unite countries' efforts to combat global environmental challenges. This means that countries can jointly develop and implement sustainable production standards,

share best practices and technologies, and coordinate their efforts to achieve global goals to reduce greenhouse gas emissions and conserve natural resources.

An example of an initiative that corresponds to this principle is the EGD (European Commission, 2019). This strategy, proposed by the European Commission, is aimed at achieving sustainable development in the EU and includes a wide range of measures aimed at reducing the impact of production on the environment. EGD covers collaboration with other countries, sharing experiences and technologies to contribute to global efforts to combat climate change and preserve biodiversity. This initiative demonstrates how cooperation and information sharing can help countries achieve common sustainable development goals through green production.

All these principles have positive consequences and improve the situation by reducing the negative impact of industrial enterprises on the environment. However, there are certain problems and obstacles in the process of transition of post-industrial society to the principles of green production.

Obstacles to green production in a post-industrial society

The main limitations and problems in the transition to the principles of green production include: economic restrictions, lack of a clear regulatory framework, technological obstacles, specifics of mentality, unwillingness of enterprises to work for the future, low level of environmental awareness and underdeveloped infrastructure (Söderholm, 2020). Thus, one of the main obstacles is the high costs of switching to green production. Manufacturing companies and governments often face large investments in the introduction of new technologies and green practices, which can put pressure on the economy. In addition, many countries do not have clear regulations governing green production, which may lead to a lack of incentives for businesses to adopt green practices and technologies. However, if businesses decide to switch to green production, implementing new technologies can be technically challenging and require significant investment in research and development. Not all industries are ready or can quickly move to a more sustainable approach. Notably, the introduction of changes in production processes and management requires a change in the mentality of both managers and employees of enterprises. Resistance to innovation and fear of losing jobs can also be significant obstacles.

In addition, the introduction of new technologies, changing strategies and approaches, and management require not only time but also financial costs. Many businesses and governments have a short-term focus and are more interested in short-term profits than in investing in green initiatives that may not generate immediate profits, which poses another challenge in the transition of businesses to green production principles. The Ukrainian manufacturing sector also faces a number of challenges and obstacles in the transition to green production, which are compounded by a certain number of unique challenges, including the consequences of Russia's war against Ukraine (Tab. 1).

Thus, Ukraine faces limited financial resources for the introduction of green technologies and the creation of infrastructure for renewable energy. The country

Table 1
Specifics of Ukrainian challenges of transition to green production in comparison with international experience

Specifics of challenges and problems	International status	Ukrainian status
Costs of switching to green production	Public investment and financial programmes to support green production	Insufficient investment support for green production
Complexity of implementing new technologies	Complexity of implementation is justified by the lack of qualified personnel and limited infrastructure	Low level of implementation of green innovations and lack of the necessary amount of research
Corruption factors	Open control and production system	Presence of corruption schemes, unfairness, and lack of transparency in the allocation of resources and influence on decision-making
Factors of public consciousness	High awareness and public participation in decision-making	Low public awareness of green issues and little public influence on decision-making processes

Source: compiled by the authors.

needs significant investment in the field of sustainable development. Many manufacturing enterprises have outdated and energy-intensive infrastructure that is difficult to upgrade. This makes it difficult to reduce energy consumption and implement energy-efficient technologies. In addition, the introduction of green production principles becomes a delayed problem, since the main goal of the state is to preserve production and infrastructure facilities. The war has led to the destruction of infrastructure and reduced economic activity in the country, creating additional uncontrolled challenges.

Moreover, with the existing regulatory framework, Ukrainian legislation still does not have a clear form. According to this, Ukraine needs to develop regulations and standards for green production. The lack of relevant regulations makes it difficult to implement sustainable practices. The Law of Ukraine No. 1818–IX "On Energy Efficiency" (2023) does not offer comprehensive guidance on more comprehensive green production criteria. Instead, it focuses exclusively on raising energy efficiency standards. Comparably, the Law of Ukraine No. 555–IV "On Alternative Energy Sources" (2023) is restricted to the energy industry, while the Decree of the President of Ukraine No. 722–2019 "On the Sustainable Development Goals of Ukraine for the period up to 2030" (2019) establishes high-level national sustainable development targets. These legislative frameworks demonstrate Ukraine's dedication to sustainability principles. Yet, they do not provide binding rules that manufacturing companies can adhere to in order to reduce their environmental impact at every level of their business activities. It is difficult for Ukrainian industries to develop complete sustainable manufacturing strategies and align with global best practices due to the lack of clearly defined green production standards, emissions restrictions, resource efficiency benchmarks, and reporting duties. Enacting comprehensive and coherent legislation is crucial in accelerating the widespread shift towards ecologically responsible industrial growth.

Corruption and lack of transparency are also serious problems in Ukraine, which can significantly complicate the development of green production. Corruption in government institutions can lead to excessive bureaucratic procedures, dishonest practices, and extortion of bribes, making it difficult to implement green initiatives and green technologies. Businesses wishing to adopt sustainable practices may face complex procedures, long registration deadlines, and uncertainty about regulatory compliance. In the absence of transparency and openness in decision-making and resource allocation processes, there may also be a risk of choosing uncompetitive and environmentally unacceptable projects. Such projects may waste budget funds, lead to a negative impact on the environment, and do not contribute to the development of green production (Ketners, 2020). However, despite these difficulties, Ukraine is implementing anti-corruption reforms and increasing transparency aimed at creating a favorable environment for the development of green production. Despite these challenges and obstacles, the transition remains an important challenge for sustainable development and the conservation of natural resources in a post-industrial society.

Implementation of green production principles in various industries

Sustainable development involves the introduction of green production in all areas of life. The agricultural sector is an important sector of the economy, where the introduction of green production principles is of great importance for sustainable development and food security (Yu et al., 2020). The principles of green production in the agricultural sector consider environmental, economic, and social aspects aimed at reducing the negative impact of agriculture on the environment and increasing productivity (Yatsiv et al., 2022). In this context, green production in the agricultural sector includes aspects such as balanced use of resources, reducing the use of chemical fertilizers and pesticides, maintaining soil fertility, and obtaining support from local communities. The use of environmentally conscious production methods in the agricultural sector aims to balance the needs of agricultural production with the importance of preserving the environment.

Efficient use of resources is another important part of green production. This involves the rational use of water, land, and other natural resources, reducing waste and minimizing losses during the production and processing of agricultural products. An important element is the optimization of irrigation systems to reduce water consumption. Another aspect is limiting greenhouse gas emissions, which contributes to the fight against global warming and climate change. In addition, the introduction of modern methods of energy conservation, the use of renewable energy, and the optimization of transport and logistics also helps reduce energy consumption and greenhouse gas emissions, while contributing to sustainable development and environmental conservation (Khodakivska et al., 2023).

Industry plays a key role in global production, but it also has a significant environmental footprint. The industry reduces the negative impact on the environment by controlling the release of harmful substances into the air and water. To achieve this goal, filters, catalysts, and other technologies are used to reduce

pollution and improve the quality of emissions. Moreover, green production in industry involves optimizing the use of energy and reducing energy consumption, which is carried out through the use of energy-efficient technologies, improving heating, ventilation and air conditioning systems, and the use of renewable energy sources. Another effective area in the transition to the principles of green production is the use of modern technologies. Introduction of modern technologies, such as the Internet of Things (IoT), artificial intelligence (AI) and automation, which allows enterprises to optimize production, track and predict costs and resource reserves, reduce financial costs, and the level of negative impact on the environment (Enyoghasi & Badurdeen, 2021).

The principles of green production also have important applications in the energy sector. They are aimed at reducing the negative impact on the environment by reducing greenhouse gas emissions and improving the efficiency of energy production and use (Borowski, 2021). One of the main principles of green energy production is the transition to renewable energy sources such as solar, wind, hydroelectric, and biomass (Linchenko et al., 2022). In Ukraine, which has a great potential for renewable sources, such a transition can be made through the development and implementation of appropriate technologies, but it can be achieved only after the complete end of the war and hostilities, during the reconstruction of the country. Now, in the context of damaged and destroyed infrastructure, it is important to create new and restore existing energy networks based on green standards.

Factors of influence and implementation of the mathematical model of decision-making in green production

Green production decision-making in a post-industrial society requires careful analysis and consideration of various factors that determine sustainability, and decision-making that meets environmental, economic, and social needs (Savchuk, 2023). Assessing the environmental impact of production is an important component of decision-making. This includes analysis of emissions and pollution, consumption of natural resources, and impacts on biodiversity. Factors such as greenhouse gas and water protein emissions can be key indicators of decision-making. Economic factors also play an important role in decision-making. Comparing the cost of green production with conventional methods can be crucial for decision-making. It is necessary to analyze the costs of production efficiency, materials and labor. In addition, decision-making should consider the social consequences for the community and society. Taking into account working conditions, the impact on consumer health and safety, and interaction with local communities are important aspects.

Additional factors include the development of innovation and technology adoption, political influence, the number of natural resources available, local and global competition, and the forecast of long-term consequences. Thus, decision-making in the field of green production requires the consideration of all these factors, ensuring a balance between environmental, economic and social aspects to achieve sustainable development in a post-industrial society. A key component of the current research was the development of a mathematical model of decision-making in the field of green production in a post-industrial society. The development of the model included several important steps that allowed the authors to create a tool for evaluating and optimizing production strategies, considering various aspects, including environmental, economic, and social ones.

A key step in developing a mathematical model for decision-making in green production was to formalize the problem. This stage defined the main parameters, constraints, and goals that the model should consider. An important goal of this stage was to create a mathematical expression that would reflect the overall structure of the problem and the relationships between its components. As a result, a model was developed that considers 3 main groups of factors of influence: economic, social, and environmental. It is important to understand that three groups of factors of influence contain a large number of variables, which will lead to an assessment based on the proposed model individually for each current situation or task, and for each enterprise. The model is aimed at determining the optimal areas of decision-making, by determining the existing deviation of the indicator from the indicator taken as ideal. Thus, the model highlights ways to minimize the actions of negative factors affecting production, and provides an opportunity to optimize production strategies depending on the tasks put forward. The weight coefficients of each of the float factors are calculated in accordance with the main purpose of the assessment. In other words, the optimization criterion should also be defined in accordance with specific goals and objectives. For example, if the main goal was to reduce the impact on the environment, then the optimization criterion may be aimed at minimizing the environmental impact. If the main goal was economic benefit, then the criterion can determine the minimization of costs or the maximization of profit.

The final stage in the development of the mathematical model was the analysis of the sensitivity and flexibility of the model. This stage was important in

the context of understanding how reliable the model is and how it can be applied in different situations, with different parameters or constraints that affect decision-making results. Sensitivity analysis involved studying how changes in the initial data affect the final results of the model. For example, by changing the values of environmental indicators or production costs, it is possible to determine what changes in the optimal production strategy can occur and what impact they will have on the state of the environment. Sensitivity analysis determines which parameters are critical for the model and require special attention. In addition, the flexibility analysis consisted of studying the possibility of modifying the model in the event of changes in conditions or constraints. For example, if new environmental standards are emerging or consumer demand is changing, how difficult or easy can the model be adapted to these changes? Flexibility analysis determines whether the model is adaptive and capable of change.

An important part of this stage was determining which parameters or constraints could be changed without compromising the basic model structure and optimization results. Thus, it was determined that the model can be edited according to current requirements, considering all relevant factors and goals. Thus, for example, when comparing two products of an enterprise from the standpoint of the optimal choice of a production strategy within the framework of green production, the model should be calculated using two options:

Option 1:

$$F(X_{B1}) = (k_1 \cdot E(X_1) + k_2 \cdot C(X_1) + k_3 \cdot S(X_1)) + (k_1 \cdot E(X_2) + k_2 \cdot C(X_2) + k_3 \cdot S(X_2)) \quad (2)$$

Option 2:

$$F(X_{B2}) = (k_1 \cdot E(X_2) + k_2 \cdot C(X_2) + k_3 \cdot S(X_2)) + (k_1 \cdot E(X_1) + k_2 \cdot C(X_1) + k_3 \cdot S(X_1)) \quad (3)$$

A special feature of this form of calculation model is the influence of different criteria for both goods (for example, the cost of production of the first and second products, or production volumes). As a result of the calculation, an inequality will be obtained, where the value of one of the calculation options ($F(X_{B1})$ or $F(X_{B2})$), will be lower than the other option, then the minimum option will be considered optimal, and will become the main one for forming a production strategy. Thus, the analysis of the sensitivity and flexibility of the model helped to determine how reliable and applicable the mathematical model is for decision-making in green production, and to determine that parameters or constraints require special individual calculation in each individual case. This knowledge became the basis for further research and improvement of the model. As a result of the analysis of the main aspects of green production in a post-industrial society, an opportunity to summarize the main areas and challenges for the transition to sustainable and environmentally sound production was provided. First of all, the considered basic principles of green production indicate the importance of environmental, economic, and social approaches to production, and the need for balanced consideration of these aspects in decision-making.

However, there are barriers and challenges to green production. Taking them into account and overcoming them requires effort and resources. Especially in Ukraine, where the transition to green production is complicated not only by common challenges, but also by problems related to war and economic instability. However, the introduction of green production principles in the agricultural and industrial sectors, as well as in the energy sector, can be an important step to reduce the negative impact of production on the environment and ensure sustainable development. The mathematical model of decision-making in the field of green production, developed as part of this study, creates a tool that allows considering various aspects when making decisions. It allows calculating the impact of various production strategies on environmental, economic and social indicators, contributing to the implementation of a rational and reasonable choice of production strategy (Strapchuk & Mykolenko, 2022).

Addressing the results of previous studies

The analysis of the principles of green production and barriers to their implementation in post-industrial society will provide an opportunity to carefully consider the advantages and disadvantages of green production in the context of current social and economic realities. A large number of scientists are engaged in studying the principles of green production, in the context of the development of society. Tan et al. (2021) consider the importance of the role of green production. The researchers argue that green bio-production has the potential to become a key tool for reducing greenhouse gas emissions and achieving climate neutrality. The authors consider green production in the agricultural sector, emphasizing that it can offer a number of benefits, including reducing greenhouse gas emissions, improving energy security, and creating new jobs. Its application covers biofuels, biochemicals and bio-products, which can help reduce the environmental impact and improve product quality. However, it is emphasized that green bio-production faces challenges such as high imple-

mentation and maintenance costs, unstable supplies, and environmental challenges that require further research and development to achieve greater success.

The study covers the agricultural sector and the analysis of the main trends in green production in it. It should be noted that the results of the study really confirm the high potential for implementing "green" initiatives in this industry. The best solution may be to balance the use of resources, reduce the use of chemical fertilizers and pesticides, maintain soil fertility, use renewable energy, and optimize transport and logistics. However, it is worth noting that in the modern conditions of Ukrainian reality, in the context of the Russian military invasion, the use of these tools becomes an extremely difficult task. Military events have caused great destruction in the agricultural sector and significantly restricted access to some resources and infrastructure (Khakhula et al., 2024; Khodakivska & Voronkî-Nevidnycha, 2023). However, with a significant amount of foreign investment and support, it is possible to restore the industry and accelerate the transition to alternative energy sources, which will contribute to the restoration and development of the Ukrainian agricultural sector and green bio-production after the war.

Ukraine faces big challenges in the energy sector because of the war. Ukrainian scientists Khomyn et al. (2023) note that the energy transition is necessary for the sustainable development of the Ukrainian economy, as it can lead to a reduction in greenhouse gas emissions, increase energy efficiency, and create new jobs. The researchers report that the war led to significant damage to the infrastructure of the energy sector of Ukraine. In particular, power plants, pipelines, oil refineries, and other facilities were damaged, which led to a decrease in energy production and an increase in energy prices. Scientists also point to the fact that the war changed the geopolitical situation in Europe, which led to an increase in Ukraine's dependence on energy imports from EU countries. Thus, it is clear that the war and military operations on the territory of Ukraine suspend the introduction of the principles of green production in most industries. However, with the support of the state and attracting a sufficient amount of investment, Ukraine is able to restore its production potential and accelerate the transition to "green" principles and tools.

Italian researchers Morelli et al. (2022) emphasize the high potential of implementing Industry 4.0 technologies, such as the Internet of Things (IoT), Big Data Analytics, and AI, which can be used to improve the efficiency and sustainability of power systems. Thus, the researchers argue that Industry 4.0 technologies can make power systems more efficient, sustainable and flexible. The development and implementation of smart energy systems that use these technologies is an important step towards a sustainable future. The current study covers a cursory overview of potentially effective Industry 4.0 systems, but does not identify them as the basis for making decisions about building production in accordance with "green" principles. However, it should be noted that this area can be effective and requires additional research. In general, the international scientific community agrees that the definition of green innovation and production principles has such basic characteristics as reducing the negative impact on the environment, improving energy efficiency, using renewable resources and environmentally friendly technologies. Despite all the positive impact, one cannot ignore the main problematic aspects of implementing green production. Therefore, Yin & Yu (2022) identify key issues such as cost, technological complexity, risk, and resistance to change.

The study also highlights certain economic constraints (lack of funding), lack of a clear regulatory framework, technological obstacles, mentality and underdevelopment of infrastructure (or, in the case of Ukraine, damage and destruction of infrastructure). All these factors act as barriers to the transition of production to more environmentally friendly principles and reduce the effectiveness of implementing "green" innovations. Takalo et al. (2021) distinguish three main types of green innovation: product innovation, process innovation, and use-oriented innovation. These types are based on introducing new products that are more environmentally friendly than existing ones, introducing new processes that use fewer resources and generate less emissions, and providing new services or business models that enable consumers to use resources more efficiently.

Current study has shown that today consumers are becoming more conscious and eager to use eco-friendlier products and services. Considering the needs of the market and the desire to reduce the negative impact on the environment, enterprises need to have optimal decision-making mechanisms regarding production strategies. To provide a promising assessment tool, a mathematical model of decision-making in the field of green production was developed. This model considers all variable factors and can be edited according to current goals. An alternative version of the production optimization model can be considered a mathematical model developed by Bachar et al. (2022). The researchers created a model that optimizes the production, marketing, and processing of products in order to minimize costs and emissions. The model considers the following factors: variable demand, partial outsourcing, and recycling. Demand for products can change over time, which can lead to a shortage or oversupply of

products. The model considers variable demand to ensure optimal production levels. Partial outsourcing can be used to meet the demand for products that cannot be produced independently, and calculating this indicator allows minimizing costs. Recycling can be used to reduce the amount of waste.

Notably, both models are aimed at minimizing costs and emissions, but they use different approaches and optimization criteria. First, the model developed as part of the current study pays attention to green production and considers the environmental, economic and social aspects of production. It considers the environmental performance and social impacts of each strategy, contributing to sustainable development and customer satisfaction. The model by Bachar et al. (2022) is more focused on optimizing production and costs, and less on environmental aspects. Second, both models consider variable demand, but the developed model focuses on optimal production of green products. The model also considers partial outsourcing and processing, which can be useful to meet demand for products that cannot be produced in-house. The proposed model focuses on sustainable production and sustainable consumers, while the mentioned model is more focused on optimizing the efficiency of specific industries. As a result, the choice between these models will depend on the specific goals and priorities of the production enterprise.

In conclusion, it should be noted that when making decisions in the field of green production in a post-industrial society, all market trends and requirements, enterprise goals and existing obstacles should be taken into account. It is possible to make optimal and effective decisions only under the conditions of detailed analysis and evaluation.

Conclusions

In accordance with the main goal and the tasks set, the study considered a number of key aspects of the introduction of green production in post-industrial society, in particular, in the Ukrainian context. It is determined that these aspects contain not only the definition of the basic principles of green production, but also the identification of barriers and challenges that complicate this process. As a result of the study, it was found that green production has great potential for achieving environmental friendliness of production and sustainable development. Defining the basic principles of green production helps to emphasize the importance of preserving the natural environment and implementing production that does not harm the environment and society. Through the analysis of barriers and challenges, it was found that the manufacturing sector faces a number of difficulties, including economic, technological, and socio-cultural problems. In addition, the study highlights the influence of factors that are unique to Ukraine, such as low public consciousness and the impact of military operations on infrastructure. These factors make the transition to green production even more difficult. However, developing a mathematical model for decision-making can be a useful tool for optimizing production and reducing environmental impact. This model can help to analyze effective strategies and consider the specifics of Ukrainian conditions.

The main result of the study was the development of a mathematical model of decision-making. The developed mathematical model is designed to solve complex decision-making problems in the field of green production within a post-industrial society. Its main goal is to optimize production, in particular, to minimize the impact on the environment and optimize costs. This model considers many different factors, such as environmental indicators, production costs, and social requirements, and allows making optimal decisions for businesses and industries looking for sustainable production. The mathematical model can be used as a tool for developing and implementing green practices and technologies that contribute to achieving sustainable production and minimizing environmental impacts. The effectiveness of the proposed mathematical model lies in its ability to provide optimal decision-making results in complex situations that consider many different factors and can be added or changed depending on current tasks and goals. The use of the model can enable enterprises and industries to reduce their environmental impact, increase production efficiency and improve product quality, which can make the proposed model an important tool for achieving sustainable development in today's post-industrial society, where environmental and economic issues are becoming more relevant. It is also worth noting that working in the field of green production requires a comprehensive approach and cooperation of various actors, from the government and business to the public. The introduction of green production in a post-industrial society, in particular in Ukraine, should be a priority, as it is important for ensuring sustainable development, reducing the negative impact on the environment and improving the quality of life.

The results of the study contribute to the development of green production and promote the global discussion on sustainability and environmental sustainability. Additional research may be aimed at identifying best practices for green production for specific industries and regions, and to consider the impact of green technologies on the environment and sustainability of production.

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