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CHALLENGES OF POST-WAR SUSTAINABLE DEVELOPMENT OF UKRAINE - EU METALLURGICAL PRODUCTS SUPPLY CHAINS

Dmytro Bugayko, Mariia Hryhorak, Mykhaylo Katsman, Oleksandr Zaporozhets, Anton Borysiuk. "Challenges of Post-War Sustainable Development of Ukraine - EU Metallurgical Products Supply Chains". *In the context of the current transformation of the global economy, the concept of sustainable supply chains is gaining strategic importance for countries from both the demand and supply sides. The European Union, having announced a course to achieve climate neutrality by 2050 and implementing the European Green Deal, has significantly strengthened the requirements for imported products, including requirements for environmental, social and economic sustainability components at all stages of the supply chain. Metallurgical products, in particular steel and semi-finished products, are a basic component of many strategic sectors of the EU economy - construction, mechanical engineering, transport and energy infrastructure. At the same time, steel production is one of the largest sources of greenhouse gas emissions in industry, which necessitates increased attention to the sources of supply and characteristics of metallurgical products in terms of their carbon footprint and compliance with sustainable development standards. The article is devoted to the development of regulatory requirements and the determination of prospects for the integration of sustainable supply chains of metallurgical products from Ukraine to the EU in the post-war period.*

***Keywords**:* supply chains, sustainable development, metallurgical products, green logistics, transport

Дмитро Бугайко, Марія Григорак, Михайло Кацман, Олександр Запорожець, Антон Борисюк. «Виклики післявоєнного сталого розвитку ланцюгів постачань металургійної продукції Україна - ЄС». *У контексті сучасної трансформації світової економіки концепція стійких ланцюгів поставок набуває стратегічного значення для країн як з боку попиту, так і з боку пропозиції. Європейський Союз, оголосивши курс на досягнення кліматичної нейтральності до 2050 року та реалізувавши Європейський зелений курс, значно посилив вимоги до імпортної продукції, включаючи вимоги до екологічних, соціальних та економічних складових стійкості на всіх етапах ланцюга поставок. Металургійна продукція, зокрема, сталь та напівфабрикати, є базовим компонентом багатьох стратегічних секторів економіки ЄС – будівництва, машинобудування, транспортної та енергетичної інфраструктури. Водночас, виробництво сталі є одним з найбільших джерел викидів парникових газів у промисловості, що вимагає посиленої уваги до джерел постачання та характеристик металургійної продукції з точки зору її вуглецевого сліду та відповідності стандартам сталого розвитку. Статтю присвячено розвитку регуляторних вимог та визначенню перспектив інтеграції сталих ланцюгів постачань металургійної продукції з України до ЄС у повоєнний період.*

Ключові слова: ланцюги поставок, сталий розвиток, металургійна продукція, зелена логістика, транспорт.

Introduction. Therefore, for the EU, the relevance of forming sustainable supply chains is explained by several key factors:

1. Decarbonization of the EU economy and industry, which is impossible without the involvement of raw materials and materials with a low carbon footprint.

2. Ensuring strategic autonomy and reducing dependence on unstable or risky sources of supply.

3. Implementation of regulatory initiatives, such as the Carbon Border Adjustment Mechanism (CBAM) and the Corporate Due Diligence Directive (CDRDD), which create a legislative framework for controlling the sustainability of supply chains.

On the other hand, for Ukraine, the issue of sustainable supply chains is not only an external challenge, but also an opportunity for strategic economic integration and strengthening its own competitiveness. Ukraine has historically been a significant supplier of metallurgical products to the EU, and despite the negative impact of the war, it remains an important player in the market of raw materials and semi-finished products. In addition, geographical proximity, the presence of its own iron ore resource base, political rapprochement with the EU and the desire for post-war economic recovery make integration into sustainable supply chains not only expedient, but also a necessary condition for the preservation and development of Ukrainian export potential.

In general, sustainable supply chains are relevant for both the EU and Ukraine due to the combination of the following strategic factors:

- the global trend towards decarbonization and greening of the economy;
- the EU's need to diversify sources of supply of metallurgical products;
- Ukraine's desire to maintain its position in the EU market and adapt to new regulatory requirements;
- a mutual interest in the development of transparent, reliable and sustainable supply chains that meet the principles of sustainable development, social responsibility and environmental safety.

Thus, the sustainable nature of metallurgical supply chains is not only a pressing challenge for Ukraine and the EU, but also one of the key tools for ensuring economic sustainability, energy security, and climate-neutral development of both sides.

The purpose of the article. To analyze the challenges, regulatory requirements and prospects for the formation of sustainable supply chains of metallurgical products between Ukraine and the European Union in the context of the post-war reconstruction of the Ukrainian economy.

Research objectives:

1. To identify the theoretical foundations of the concept of sustainable supply chains and their specifics in the metallurgical industry.

2. To consider the main EU regulatory initiatives that affect the sustainable export of metallurgical products from Ukraine (in particular, CBAM and CDRDD).

3. To analyze the main challenges of the post-war period that affect the formation of sustainable supply chains of metallurgical products.

4. To investigate the logistical aspects of sustainable supply chains and their role in increasing the competitiveness of Ukrainian metallurgy in the European market.

5. To assess the prospects for Ukraine's integration into the EU's green supply chains and to offer recommendations for their development in the context of post-war reconstruction.

Literature Review. The literature review shows that the consequences of aggression against Ukraine are felt in all sectors of the economy, but most of all in export-oriented industries. In this regard, the issue of post-war recovery of the Ukrainian economy and ensuring its competitiveness is attracting increasing attention from researchers. Scientific works [1-2] emphasize that the recovery of the national economy is inextricably linked to the tasks of sustainable development, as well as the possibilities of attracting external financing for the implementation of "green" projects. Considerable attention is paid to the issues of infrastructure modernization, the introduction of energy-efficient technologies into industry, and the development of innovative production practices [3]. Researchers [4] emphasize that the economies of Ukraine and the EU countries have a high level of interdependence, which necessitates the need for post-war reconstruction on the basis of integration into the European economic space. In particular, the literature emphasizes achieving the goals of the circular economy, including legal, economic, and organizational mechanisms for managing recovery processes. Some authors [5, 6] draw attention to the role of legal regulatory instruments and environmental standards that should contribute to the synchronization of Ukrainian economic policy with the European one.

A special place in the review of scientific publications is occupied by studies devoted to the metallurgical industry, which is one of the leading export-oriented sectors of the Ukrainian economy. The works [7, 8] note that increasing the competitiveness of metallurgy is a strategic task for both the state and business. The authors emphasize that effective reconstruction is possible provided that the institutional capacity of the government is strengthened in coordinating decarbonization policies and developing dialogue between industry, business and society.

In modern literature, there is also interest in the potential role of Ukraine as a key supplier of iron ore suitable for the production of direct reduction iron (DRI). Researchers [9, 10.] predict that in the conditions of decarbonization of the metallurgical sector of Europe, the demand for such products will grow. At the same time, the works [11] emphasize that in order to realize this potential, it is necessary to transition to open innovation models that will allow integrating Ukrainian enterprises into global value chains and provide access to international technologies and financial resources.

A separate layer of research focuses on the issue of forming sustainable supply chains for metallurgical products. Scientists [12, 13] emphasize that ensuring reliability and diversification of supplies is of strategic importance not only for Ukraine, but also for the EU, which seeks to reduce dependence on individual markets.

Despite the presence of a significant number of publications devoted to the issues of post-war reconstruction and the prospects for the development of Ukrainian metallurgy, a literature analysis demonstrates the presence of research gaps. The aspects of the organization and functioning of sustainable supply chains for metallurgical products from Ukraine to EU countries in the context of rebuilding the economy on the principles of sustainable development remain insufficiently studied. It is precisely this issue that requires further thorough scientific research.

Presentation of the main results. Theoretical foundations of sustainable supply chains for metallurgical products. Sustainable (green) supply chains in the metallurgical industry have a number of features, which are due to both the specifics of the industry itself and high expectations for the decarbonization of the industry on a global scale. Metallurgy is one of the most energy- and resource-intensive sectors of the economy, where production processes are accompanied by significant greenhouse gas emissions, high water consumption, the use of fossil fuels and the generation of waste. According to international studies, metallurgy accounts for 7–9% of global CO_2 emissions, which makes this industry one of the key targets of the "green transition" policy in the European Union and other regions of the world. In this context, sustainable supply chains of metallurgical products are characterized by a complex multi-level structure, which includes such elements as extraction and transportation of raw materials (iron ore, coal, scrap), production processes (processing, smelting, rolling), logistics of finished products, as well as recycling and reuse of metal. A feature is that a negative environmental footprint is formed not only at the stage of steel production, but also at the stage of transportation and supply, which is especially relevant for Ukraine, given the complex geography of supplies to EU countries.

An important characteristic of sustainable supply chains in metallurgy is the need to implement the latest "green" technologies, such as electrometallurgy based on renewable energy, the use of hydrogen instead of carbon for iron recovery processes (DRI - Direct Reduced Iron technology), closed water supply cycles, effective waste management and an increase in the share of secondary raw materials - scrap metal. Therefore, manufacturers seeking to remain competitive in EU markets must not only declare sustainability, but also prove it through product certification, supply chain transparency and compliance with European initiatives such as the Green Deal, CBAM and CDRDD.

In addition, supply chains in the metallurgy industry are often international and include a large number of participants - from suppliers of raw materials to end users of finished products in mechanical engineering, construction and other industries. This leads to high requirements for coordination, information transparency and corporate responsibility standards. This is especially relevant for Ukrainian metallurgy, which is focused on exports, in particular to the European Union, where consumers are increasingly paying attention not only to quality and price, but also to the environmental and social footprint of products.

Thus, the peculiarity of sustainable supply chains in metallurgy is their complexity, resource and energy intensity, dependence on geographical and logistical factors, as well as the critical need for modernization of technologies and implementation of international standards of sustainable development to maintain competitiveness in global markets.

The EU regulatory environment and its impact on sustainable exports of Ukrainian metallurgy. The analysis of the EU regulatory environment shows that over the past decade the concept of sustainable supply chains has transformed from a corporate initiative of individual companies into a mandatory regulatory standard, which is increasingly being applied at the interstate level. The European Union regulatory environment in the field of sustainable supply chains is one of the most progressive in the world and has a direct impact on supplier companies from third countries, in particular from Ukraine.

The foundation of modern European policy in this area is the European Green Deal initiative, adopted in 2019, which envisages the transition of the EU to a climate-neutral economy by 2050 [14]. According to this strategy, all sectors of the economy, including industry and international trade, should transform their supply chains to reduce their carbon footprint, increase energy efficiency and ensure social responsibility. One of the key regulatory mechanisms of the Green Deal, which directly affects the supply chains of metallurgical products, is the Carbon Border Adjustment Mechanism (CBAM), which began operating in a test mode in October 2023 [15]. The CBAM provides for the gradual introduction of an import levy on products with a high carbon footprint, including steel, iron, cement, fertilizers and other goods. The main goal of this mechanism is to protect European producers from "carbon leakage" and to encourage EU partners to modernize their production processes in accordance with environmental standards. For Ukrainian metallurgical enterprises, this means the need to ensure transparent accounting of CO2 emissions at all stages of production in order to maintain access to the European market on competitive terms. Another important element of the regulatory environment is the CDRDD - the EU Directive on Corporate Sustainability Due Diligence, which was finally agreed in 2024 [16]. It establishes an obligation for large companies operating in the EU market to carry out a comprehensive check of the sustainability of their supply chains, including environmental, social and human rights aspects. The directive applies not only to European companies, but also to their suppliers from third countries. Thus, Ukrainian steel companies that want to remain in the supply chains of leading European manufacturers must confirm compliance with environmental standards, principles of social responsibility, human rights and labor standards at all stages of the production process [17].

The combination of regulatory initiatives such as the Green Deal, CBAM and CDRDD creates new rules of the game for international supply chains, where sustainable development, decarbonization and transparency become not a competitive advantage, but a prerequisite for participation in the European market. For Ukraine, this is not only a challenge, but also an opportunity to integrate into the EU's strategic green chains, provided that the national industry adapts, introduces modern environmental technologies and builds transparent, responsible supply chains for metallurgical products [18, 19].

For several years now, Ukraine has been actively discussing how the EU regulatory environment could affect the development of the metallurgical industry and its export potential. In particular, in October 2024, GMK center published a report "How the European SBAM could weaken the Ukrainian economy" [20], which concluded that the Ukrainian metallurgical industry will suffer the most from CBAM, since 93% of Ukrainian exports covered by CBAM are iron and steel products. CBAM will lead to a gradual reduction in free allowances in the EU ETS system. For example, in 2026, it is planned to cancel 2.5% of free allowances, in 2030 - 48.5%, and in 2034 - 100%. A reduction in free allowances will lead to an increase in carbon prices in the EU ETS and an increase in CBAM payments. The higher the CBAM costs, the greater the losses for the Ukrainian economy. Due to the European CBAM, Ukraine may stop exporting cement, fertilizers, cast iron, square billets and long products after 2030. In this case, export losses will exceed $1.4 billion, of which losses in exports of MMC products will amount to $1.3 billion. According to revised estimates for the current year, potential investment losses in the Ukrainian economy in 2026-2030 may amount to $2.7 billion, and potential losses from exports during this period will amount to $4.7 billion [21]. GDP losses will be even greater due to inter-sectoral linkages in the Ukrainian economy. For example, the metallurgical sector affects the activities of the coal and coke chemical industries, mechanical engineering and the service sector. The metallurgical industry is a key driver of development in the regions where production facilities are located.

There is no doubt that the Russian invasion and the resulting damage to Ukraine meet the conditions of Article 30.7 of the Regulation. The Russian invasion, while being beyond Ukraine's control, has caused significant and devastating consequences for economic and industrial infrastructure. Direct losses alone as of early 2024 amounted to $155 billion. Losses are increasing with each passing day of the war. This time has been lost in adapting Ukraine's economy to the goals of the "green" transition. In addition, Ukraine will have limited opportunities to stimulate decarbonization in the post-war period. Excluding Ukraine from the CBAM under Article 30.7 is a logical step and will be a test for the mechanisms envisaged by European legislators in regulating the CBAM.

Ukrainian industry experts believe that Ukraine should take advantage of the provisions of Article 30.7 of Regulation (EU) 2023/956 of the European Parliament and of the Council of 10.05.2023, on the exclusion of third countries from obligations under the CBAM The Russian invasion, being beyond the control of Ukraine, has caused significant destructive consequences for the economic and industrial infrastructure. According to Reuters, as of February 2025, direct losses to Ukraine from Russian aggression are estimated at $176 billion. This amount includes direct physical destruction of buildings and infrastructure, as well as the impact on the lives and livelihoods of citizens. Losses are growing with each passing day of the war, which has been going on for 2 years and 7 months at the time of this report. This time has been lost to adapt Ukraine's economy to the goals of the "green" transition. In addition, in the post-war period, Ukraine will have limited opportunities to stimulate decarbonization. Excluding Ukraine from the CBAM under Article 30.7 is a logical step and will be a test for the mechanisms envisaged by European legislators in regulating CBAM. Table 1 summarizes the impact of CBAM and CDRDD on the Ukrainian metallurgical industry.

Table 1 – Impact of CBAM and CDRDD on the metallurgical industry of Ukraine

Aspect	**CBAM (Carbon Border Adjustment Mechanism)**	**CDRDD (Corporate Sustainability Due Diligence Directive**
Opportunities		
1. Incentive for modernization and reduction of carbon footprint	Increasing the technological level of the industry to comply with EU requirements	Motivation for increased transparency, environmental and social responsibility
2. Access to the "green" European market	Maintaining and potentially expanding market share for "green" steel producers	Priority for responsible suppliers in the supply chains of European companies
3. Attracting investments and technologies	Chance to receive EU funding for decarbonization	Possibility to attract partnership programs and investments to improve sustainability standards
4. Deepening integration with the EU	Compliance with European climate legislation	Harmonization with EU social and environmental standards, bringing the economy closer to the EU
Threats		
1. Financial losses for non-competitive producers	Increasing export costs through carbon payments for high-CO^2 companies	Potential loss of contracts for companies that do not provide adequate transparency
2. Risk of reduced exports	Losing positions in the EU market without modernization	Exclusion from European supply chains due to non-compliance
3. Administrative burden	Need to introduce carbon footprint accounting systems	Implementation of a system of monitoring, auditing, verification of suppliers |
4. Increasing competitive pressure	Increasing competition from "green" producers from other regions	European companies can choose suppliers from countries with a better reputation in the field of sustainability

Source: compiled by the authors

An important component of the European Union's current regulatory policy in the field of sustainable development is the requirement for the introduction of Product Digital Passports (PDP), which increasingly cover industrial goods, in particular products from the metallurgical sector [22]. This tool is part of a broader EU initiative aimed at increasing transparency, environmental responsibility and traceability of supply chains in line with the objectives of the European Green Deal and the Sustainable Products Package. The issue of digital passports is most systematically enshrined in the draft EU Regulation on Ecodesign for Sustainable Products (ESPR), the adoption of which is expected in the coming years. Under the ESPR, a digital passport will be mandatory for certain product categories, including steel, aluminium and other industrial materials, containing detailed information on the origin of the raw materials, product characteristics, carbon footprint, environmental and social aspects of production, and recycling and reuse options.

In addition, the provisions on supply chain transparency and mandatory disclosure of environmental impact are contained in the Corporate Sustainability Due Diligence Directive (CSDDD or CDRDD). It explicitly requires large companies and their suppliers, including those from third countries, to demonstrate compliance with environmental and social standards at all stages of the production and logistics process, which requires the provision of supporting documents, among which digital product passports are becoming one of the key tools [23]. In the context of metallurgical products, this means that Ukrainian manufacturers seeking to maintain or expand their presence on the European market should prepare today to implement digital passports for their products. This requires modernization of information systems, implementation of internal carbon footprint monitoring, transparent declaration of materials used, as well as digital integration with European partners. Thus, digital product passports become not only a regulatory requirement, but also a strategic element in the formation of sustainable supply chains, which ensures transparency, increases trust in Ukrainian metallurgical products and creates additional competitive advantages on the European market.

Post-war challenges for sustainable supply chains of Ukrainian steel products. The Ukrainian economy is traditionally export-oriented. During the war, the EU became the main trading partner, given the blockade of Ukrainian seaports. Exports allow Ukrainian companies to continue production activities, support employment and the local economy. The steel industry is traditionally one of the key export-oriented industries of Ukraine, providing a significant share of foreign exchange earnings, employment and industrial production. According to data before the full-scale invasion, more than 80% of Ukrainian steel products were exported to the European Union and other countries, which indicate the deep integration of Ukrainian steel into global and European supply chains.

The mining and metallurgical sector (MMS) has been and remains one of the key sectors of the economy. The numbers speak for themselves. In 2021, MMS accounted for 10% of the country's total GDP. Export revenue was estimated at $22 billion and accounted for ⅓ of total exports. The enterprises employed over 130,000 people and another 530,000 in related industries. UAH 95 billion in direct taxes were paid. The full-scale invasion significantly affected the sector, as a large share of enterprises was located in the eastern regions of the country, which are temporarily occupied. In 2024, its contribution was 7.2% of Ukraine's GDP, including supply chains. In 2024, the sector's share in total exports was almost 15%.

Table 2 presents statistical data on the production volumes of the mining and metallurgical sector of Ukraine.

Table 2. Production volumes of metallurgical products in Ukraine, thousand tons

Product Types	Production volumes, thousand tons			
Years	2021	2022	2023	2024
Iron Ore	84431	31411	28823	44690
Pigment Iron	3236	1325	1249	1290
Steel	21366	6263	6228	7575
Long Rolled Products	3800	1350	1764	2028
Scrap Procurement	4100	997	1277	1749

Source: compiled by the authors based on data from GMK center

In 2024, Ukraine reached a local peak in steel exports (forecast 4.6 million tons), largely due to the growth in supplies of semi-finished products. However, the forecast for 2025 (3.9 million tons) looks less optimistic. In January-May 2025, the mining industry of Ukraine reduced iron ore exports by 12.8% compared to the same period in 2024 - to 13.54 million tons [24].

Most experts predict a further reduction in the production and export of metallurgical products in 2025 due to increasing risks and challenges for the entire mining and metallurgical complex of the country. A particularly significant risk is the decline in square billet exports. In 2024, the disparity between cheaper iron ore and expensive scrap made exports profitable. However, at the end of the year, scrap prices fell due to active exports of billets from China. This may significantly affect Ukraine's export opportunities in 2025. Table 3 summarizes the main influencing factors and key challenges and possible negative consequences that will directly affect the reduction in the volume of production and exports of MMS products.

Table 3 – Main challenges and threats for the metallurgical industry of Ukraine

Factor	Threat/Challenge Essence	Likely consequences
Continued hostilities and stagnation in the domestic market	Destruction of infrastructure, shutdown of enterprises, low domestic demand	Decline in production and investment
Competition with Russian metal in the EU	EU continues to purchase Russian metal products despite sanctions, dumping by the Russian Federation	Loss of Ukrainian exports' share in the EU market
Decrease in world prices due to increased steel exports from China	Oversupply of Chinese products puts pressure on global prices	Decline in profitability of Ukrainian exports
Deficit of coking coal and the need to import coke	Increasing production costs due to dependence on imports	Worsening of product competitiveness
Trade restrictions on the export of Ukrainian metal products (28 barriers)	Quotas, anti-dumping investigations, technical barriers	Limited access to foreign markets
Carbon border tax in the EU (CBAM)	Ukrainian products with a high carbon footprint will be subject to additional duties	Potential losses of up to $1.6 billion annually by 2030
Increase in tariffs of natural monopolies (transportation, electricity, gas, water)	Increasing cost of production	Decline in profitability, risk of closure of some enterprises
Labor shortage (15–20% of personnel mobilized)	Lack of qualified personnel, reduced productivity	Stoppage of certain production processes, slowing down of industry recovery
Complicated logistics and high logistics costs	Longer delivery times, difficulties at borders, high freight rates	Increase in the final cost of products, decrease in competitiveness

Source: compiled by the authors

Among the systemic challenges is the shortage of personnel. Wartime significantly complicated the selection and retention of qualified specialists, especially in areas with physical exertion. Despite this, we see new opportunities - women are actively involved in technical professions and often demonstrate high results. Logistics remains no less critical: extended delivery times, unstable transport costs, difficulties at border crossings.

Additional pressure on manufacturers is also created by increased logistics and energy costs. In particular, Ukrzaliznytsia plans to increase transportation tariffs again. The logistics component in the cost of cargo will increase for coal and ferrous metals - up to 1%. Thus, according to the calculations of ArcelorMittal Kryvyi Rih, the additional costs of the enterprise for logistics will amount to more than UAH 1.4 billion per year, which will reduce the competitiveness of products along the chain and may lead to a complete stoppage of production [25].

Not the least of the challenges is the problem with the supply of coking coal. Most of the domestic supply depends on the Pokrovske mine management, whose work is under threat due to hostilities. If the mine stops, metallurgists will be forced to import more expensive coal, which could significantly affect the cost of production.

Logistics aspect of sustainable supply chains. Logistics is a critically important component in the formation of sustainable supply chains, especially in the metallurgical sector, where a large mass of products, the complexity of transportation and high requirements for maintaining product quality necessitate careful organization of transport and warehousing processes. In the context of Ukraine's post-war reconstruction and increased EU requirements for environmental friendliness and transparency of supply chains, logistics acquires additional strategic importance. Starting in 2022, the war has significantly affected Ukraine's infrastructure and logistics capabilities. In particular, key railway and port facilities were damaged, which led to a decrease in the throughput capacity of transport hubs and the need to look for alternative routes. In addition, logistics costs have increased significantly due to higher fuel prices, complicated customs procedures, increased insurance tariffs and unstable transportation schedules. The main challenges/problems for the logistics aspect of Ukraine's sustainable supply chains are listed in Table. 4.

One of the key challenges for the formation of sustainable supply chains of metallurgical products from Ukraine to the European Union countries remains high logistical vulnerability, which is due to objective limitations of the infrastructure and the insufficient level of its development. In particular, one of the most critical challenges is the concentration of metallurgical product exports through a limited number of available transport corridors. Due to the destruction of port and railway infrastructure in the south and east of Ukraine, as well as the blocking of traditional sea routes, the main export flows are forced to be directed through western land crossings, such as corridors through Poland, Slovakia, Hungary and Romania. This creates "bottlenecks" at border crossing points, which leads to delays, increased costs and reduced predictability of supplies, as well as to an increase in greenhouse gas emissions.

The impact of transport logistics on the carbon footprint of metal products is one of the key criteria for compliance with European sustainability standards. Transport CO2 emissions, especially when using diesel trucks, significantly increase the overall environmental footprint of metallurgical products. To reduce the negative impact, it is advisable to use multimodal transportation, combining rail, river and sea transport, which allows optimizing routes and reducing emissions. In addition, the gradual introduction of electric transport, the use of energy-efficient warehouse solutions and "green" packaging materials creates additional value for end consumers and EU regulators.

EU transport policy is focused on increasing the role of rail transport in the freight transport system. The integration of Ukraine's railway network into the European one involves the expansion of the Eurogauge (1435 mm) to the territory of Ukraine, in particular, on the Kyiv-Kharkiv-Dnipro routes, as well as in the west and south of the country. This includes the extension of the Eurogauge from Rava-Ruska through Lviv to the border with Romania, as well as from Odessa to Chisinau. The implementation of these projects, which are part of the TEN-T network, will allow Ukraine to access financing and promote integration into the European transport system.

In June 2025, the World Bank published a report analyzing the reform of Ukrzaliznytsia, infrastructure modernization and investments in Ukraine's railways - "Ukraine's Transport and Logistics System" [26]. The study covers TEN-T, cross-border logistics, export transportation and the EU integration strategy. This report notes that Ukraine has one of the largest railway networks in Europe - over 19 thousand km, of which approximately 47% is electrified. However, about 60% of the tracks are operated beyond their standard service life, more than 35% of the switches are in unsatisfactory condition.

Table 4. Key challenges/issues for the logistics aspect of sustainable supply chains in Ukraine

Type of transport	Challenges and problems	Solutions
Maritime transport: Capacity 250 million tons per year 2. Provided 70% of the export of agricultural products, metallurgy, chemical industry and mineral fertilizers and 90% of agricultural products	– blockade of seaports by Russia; – destruction of port infrastructure (Odesa, Mykolaiv); – low throughput capacity of Danube river ports (only 10 million tons per year) and passage only for small vessels and barges; – problem of storage and transportation of containers with goods from alternative ports; – low throughput capacity of alternative ports (Constanta, Romania).	– use of the main ports of neighboring countries in Gdansk, Varna, Constanta; – construction of strategic universal transport hubs; – restoration of damaged port infrastructure.
Railway transport: 1. Brought 70-80 billion in revenue annually 2. Transportation was carried out to seaports and within the country 3. 65% of cargo was transported by rail	– 6.3 thousand km of railway network, 41 railway bridges, 21 railway stations were destroyed; – change in freight directions (to seaports changed to the western); – bureaucratic and overly regulated document flow; – the need to protect infrastructure from enemy attacks; – capacity limitations at checkpoints (sorting stations, lack of warehouses, low level of processing) and technological problems of different gauge sizes.	– development of the Eurorail from the Ukrainian side; – increasing the number of checkpoints on the border with EU countries – creation of a single portal for processing transportation documents.
Road transport provided 36% of freight transportation (244 million tons per year)	– rising fuel prices and limited availability; – increasing queues at checkpoints on the western border to 35-50 km; – increasing border crossing time to 7 days; – increasing transportation costs.	– increasing the throughput capacity of automobile checkpoints; – extending the validity of the "Transport Visa-Free"; – introducing "eQueues".

Source: developed by the authors

The war significantly accelerated the physical depreciation of assets: more than 11 thousand damaged railway infrastructure objects were recorded. The level of wear and tear of traction rolling stock and freight wagons remains critically high, which limits the capacity and productivity of the network.

Particularly critical is the lack of specialized rolling stock that is compatible with the European (narrow) gauge. The UZ rolling stock often does not meet EU standards due to differences in dimensions and technical parameters. The report indicates that both UZ and European operators face a shortage of grain trucks, refrigerators and tanks that would meet EU standards. At the same time, due to the uncertainty of future demand, European operators are not ready to invest in increasing the fleet of wagons for cross-border trade with Ukraine. This further limits the ability of rail transport to ensure the export of Ukrainian goods to the EU, especially given the need for rapid transhipment and compliance with European standards.

At the same time, integration into the EU system requires a balanced approach: instead of a massive transition to the standard 1435 mm gauge, it is proposed to develop transhipment capacities and stimulate containerization. The report emphasizes the importance of containerization and the development of multimodal logistics, which is characteristic of the transportation of products with higher added value. This indicates a potential shift in focus from the transportation of raw materials to more complex goods in the export structure. The report also emphasizes the need to reform JSC Ukrzaliznytsia and adapt the industry to the requirements of the European transportation market. In particular, this concerns the New Law "On Railway Transport", which should harmonize Ukrainian legislation with EU law and provides for the separation of infrastructure and transportation management functions.

To increase the sustainability of metallurgical product supply chains, diversification of transport routes is necessary. The use of transport corridors through Poland, Romania, Slovakia, and Hungary opens up alternative export routes, reduces the load on traditional highways, and increases delivery reliability. That is why the development of Danube ports and water transport has special potential, which allows reducing logistics costs and environmental impact.

As noted in the World Bank report, deep-water Black Sea ports will remain the main export-import "gateway" of Ukraine. Despite the development of alternative routes (Danube, roads, and railways), none of them has sufficient reserve capacity to fully replace the Black Sea route in the event of its repeated blocking. Short-term actions should focus on improving multimodal access to ports, restoring railway infrastructure, purchasing new locomotives and modernizing transshipment equipment. Despite their secondary role compared to deep-sea ports, Danube ports remain a strategic reserve and insurance logistics route for Ukraine. They provide an alternative route for exporting large-tonnage cargo over medium and long distances - through direct shipping to the Mediterranean or barge transportation to Constanta with subsequent transshipment onto ocean-going vessels. However, the current infrastructure of Danube ports does not allow for full compensation for the volumes lost in the event of restricted access to the Black Sea.

As GMK Center reported, Ukrainian seaports processed 18.5 million tons of ore cargo in 2024 [vi https://gmk.center/en/news/ukrainian-ports-handled-23-million-tons-of-cargo-in-the-first-quarter-of-2025/]. The total cargo turnover last year reached a record high of 97.2 million tons compared to 62 million tons in 2023, exports amounted to 88.1 million tons. The largest volumes of transshipment traditionally fall on the ports of Greater Odessa, which provided 20.7 million tons of cargo turnover. Another 2.3 million tons passed through the ports of the Danube region - Izmail, Reni and Ust-Dunaysk. In January-June 2025, Ukrainian seaports processed about 40 million tons of cargo, of which more than 9.3 million tons were iron ore products, and another 2.1 million tons were ferrous metals [20, 23]. For comparison: in pre-war 2021, the volume of sea transshipment in Ukraine reached 153 million tons, of which almost 38 million tons were ore cargoes, and 16 million tons were ferrous metals.

An additional factor complicating the supply chains of metal products is the increased complexity of coordination between different modes of transport and numerous participants in the supply chain. The export of metallurgical products usually involves multimodal transportation, including rail, road and sea transport. In conditions of limited capacity of individual infrastructure sections, lack of agreed schedules and insufficient integration between different modes of transport, time and financial costs increase, as well as the risks of violating delivery deadlines. This is especially critical for metallurgical products, which often have large-sized characteristics, require special transportation conditions and fast delivery to maintain competitiveness.

Another systemic problem that significantly limits Ukraine's integration into sustainable supply chains of metallurgical products to the EU is the insufficient level of digitalization of logistics processes and supply chain management. Modern requirements of the European market have long gone beyond the traditional control over the physical movement of goods. Participants in supply chains, especially in such sensitive industries as metallurgy, are expected to have comprehensive transparency and the ability to quickly track information about the origin of products, their characteristics, environmental footprint and compliance with sustainable development standards.

However, currently, in the Ukrainian metallurgy and related transport and logistics sectors, there is fragmentation of information systems. The lack of unified integrated digital platforms for all participants in the chain, weak interaction of accounting and logistics systems of enterprises, limited use of modern digital solutions for monitoring the movement of goods, automatic documentary support and data exchange significantly complicate transparency and coordination of processes. This creates room for inconsistencies, delays in delivery, increases the risk of losses and errors and, most critically, hinders compliance with modern EU regulatory requirements.

In particular, the adopted EU Directive on Due Diligence in Sustainable Supply Chains (CDRDD) directly obliges companies operating in the European market to ensure a high level of transparency and control at all stages of supply, including monitoring the social, environmental and ethical aspects of production and transportation of products. One of the key tools for implementing these requirements is Product Digital Passports (PDP), which must contain complete, reliable and up-to-date information on the origin of raw materials, production conditions, carbon footprint and environmental responsibility.

Without proper digitalization of logistics and supply chain management, the accumulation and prompt updating of such information is impossible. The lack of a transparent digital infrastructure deprives Ukrainian manufacturers of the opportunity to effectively prepare and verify digital product passports, which becomes not just a technological gap, but a strategic barrier to access the EU market.

Thus, the digitalization of logistics processes and supply chains, including the creation of unified information platforms, the integration of systems of all chain participants and the active use of cargo monitoring solutions, is critically necessary not only to increase transportation efficiency, but also to meet new EU regulatory requirements, the preparation of digital product passports and the real integration of Ukrainian metallurgy into the steel supply chains of the European market.

Solving these problems requires a comprehensive approach that includes infrastructure development, digital transformation of logistics processes and effective interstate coordination to minimize logistics risks and ensure the reliability and sustainability of supplies of Ukrainian metallurgical products to the EU.

Innovative development of multimodal supply chains is impossible without the implementation of effective transportation control tools, especially in the context of increasing complexity of global supply chains, increasing environmental standards and the need to ensure the safety of cargo. Monitoring delivery, responding promptly to emergencies, preventing illegal interference in the transportation process and minimizing the environmental impact of transportation are critical elements of modern logistics that directly affect the reliability and sustainability of supply chains.

In this context, unmanned civil aircraft systems (UAS) demonstrate significant potential for solving these tasks. Due to their mobility, high efficiency and the ability to monitor in hard-to-reach areas, UAS provide constant control over the movement of cargo, allow for timely detection of violations or threats, as well as environmental monitoring, for example, recording leaks of harmful substances or contamination of territories in the event of transport incidents.

The effectiveness of using UAS in logistics and environmental monitoring is confirmed by many years of scientific research carried out by leading domestic and international institutions. In particular, scientists from the State University "Kyiv Aviation Institute" (Kyiv, Ukraine), the National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute" (Kyiv, Ukraine) and the Institute of Aviation (ILot) (Warsaw, Poland) focus their research on issues of technical improvement, safety of use and expansion of functional capabilities of unmanned aircraft systems for the needs of transport logistics. The results of these studies create a scientific basis for the widespread introduction of UAS into the system of multimodal transportation and sustainable supply chains [27].

The environmental aspect of sustainable supply chains. Transportation of metallurgical products, in particular by rail, plays a key role in the formation of sustainable supply chains between Ukraine and the EU countries. At the same time, this type of transportation is often accompanied by environmental risks, especially in cases of transportation of specific cargoes of the metallurgical complex, such as pig iron, ferroalloys, metallurgical coke, metallurgical waste or associated hazardous chemicals used in production or transported together with metal products.

Railway transport, which is one of the basic sectors of the Ukrainian economy, provides transportation of a significant volume of cargo of various properties, which, if safety measures and precautions are not observed during their transportation, can pose a threat to transport workers, the population, and the environment. Early response to the threat of an emergency, including an ecological one, is carried out on the basis of monitoring data, environment assessment, research and forecasts regarding the possible course of events in order to prevent the further development of such a situation or mitigate its possible consequences.

Based on the analysis of the current state of transportation of dangerous goods by rail in Ukraine, it is shown that the characteristic consequences of emergency situations during the transportation of such goods are leakage (80.7%), spontaneous combustion (11.2%) and evaporation (5.6%), which necessitates the creation of a set of organizational and technical measures aimed at carrying out effective actions to reduce the harmful impact on the environment and human life of the negative factors of these situations [28]. It was revealed that there is an antagonistic contradiction between the parties to a railway emergency situation (natural and man-made factors and targeted actions of liquidation units), a feature of which is the presence of an ecological hazard of the "stay" of natural mechanisms at the place of resolving the contradiction, while the concentration of liquidation units and the organization of their actions by the operational headquarters still requires certain efforts and time.

Studies of environmentally hazardous transport events in the railway sector [29] show that such situations have a complex, sometimes latent nature of development, the final consequences of which can be explosions, fires, destruction of rolling stock and infrastructure, loss of life and large-scale environmental pollution. In particular, three typical scenarios of the development of events are:

- Slow accumulation of negative factors (for example, technical wear of wagons, violation of loading or fastening rules of metal products), which does not reach critical limits, but creates a constant hidden source of risk.
- Accumulation of negative factors with a gradual exit beyond critical limits, which can

lead to serious incidents, in particular when transporting metal products as part of mixed cargo together with flammable or chemically hazardous substances.

• Rapid accumulation of critical factors, for example, due to an emergency situation, poor-quality maintenance of rolling stock or external influence (sabotage, shelling in war conditions), which directly leads to catastrophic consequences.

In view of the above, ensuring effective monitoring of metallurgical product transportation is not only a matter of logistics optimization, but also a critical condition for reducing environmental and man-made risks. The implementation of modern digital solutions, real-time tracking systems, as well as the use of unmanned aircraft systems to monitor the movement and condition of railway cargo will allow for timely detection of dangers, forecast the development of emergency situations and minimize their negative consequences for both the economy and the environment.

In the context of metallurgical product transportation, the application of the theory of queuing systems (QS) methods is a traditional approach to modeling logistics flows, managing the load of transport nodes, as well as assessing delays, queues and the efficiency of resource allocation in transport systems [29, 30]. However, the full-scale aggressive war of Russia against Ukraine in 2022–2025 significantly changed the conditions for the functioning of logistics in the country, which necessitates a rethinking of the tasks that are solved within the framework of this theory. In particular, for the transportation of metallurgical products, which is critically important for both domestic industry and exports to EU countries, a number of new challenges arise:

• limited number of transport corridors due to the destruction of infrastructure or their congestion;

• growing competition between different types of cargo for the use of limited logistics capacities (with some cargoes having priority - for example, humanitarian aid or military support);

• frequent disruptions in schedules due to shelling, energy crises, or sudden changes in logistics due to security threats.

In wartime conditions, classic QS should be supplemented with modeling components with priorities, where certain categories of cargo (in our case, metallurgical products as a strategic export) are given an increased level of access to limited resources - ports, border crossings, freight cars, warehouses, etc. Taking into account priorities allows us to assess the impact of decisions on dispatching, rerouting or redistributing cargo flows on the overall efficiency of supply chains and their environmental footprint.

In addition, QS with priorities can be used for environmental and economic assessment: for example, to determine which logistics service scenarios (via which transport corridor, with what delays, at what load levels) lead to a smaller carbon footprint or reduced pollution risks. This is especially relevant in the context of increased environmental requirements for metal products in the EU (in particular through CBAM and CDRDD), where not only production, but also transportation is taken into account when assessing the overall sustainability of products.

In the current conditions of transportation of metallurgical products from Ukraine, especially in conditions of war and partial destruction of transport infrastructure, the problem of effective distribution of limited logistical resources has acquired critical importance. In particular, we are talking about a limited number of locomotives, wagons, port capacities and the throughput capacity of railway corridors that remain functional. In such conditions, prioritization of cargo is not only an organizational, but also an economic and strategic necessity. According to the logic, which is confirmed by the theory of priority-based queuing systems, the first right to transportation is given to cargoes that are critical for national security, defense or emergency response.

At the same time, other cargoes, including metallurgical products, which are the basis of Ukraine's export potential and one of the key areas of post-war economic reconstruction, also require a clear prioritization system. In this context, it is advisable to apply the criterion of the ratio of the cost of the cargo (economic value for the state or enterprise) to the time remaining before the deadline for delivery to the destination station or to the customer. This approach allows for the most efficient use of limited transport resources, minimize economic losses and avoid disruptions in strategically important supply chains.

This is especially true for metallurgical products that have high added value, are export-oriented and directly affect the state's foreign exchange earnings and the fulfillment of contractual obligations to European partners. Delays in their delivery can not only lead to fines and reputational losses, but also jeopardize the integration of Ukrainian metallurgy into the EU's steel supply chains.

The application of the mathematical apparatus of priority-based QS optimization allows to automate and justify these decisions. Such models take into account the real state of the infrastructure, the number of available locomotives, the downtime of cargo, the economic significance of products and time constraints, which makes transport planning as efficient and transparent as possible.

The complexity of implementing analytical methods of the theory of QS is determined by the volumetric forms of the mathematical description of their functioning. Therefore, when solving the scientific problem, it is advisable to use computer simulation methods. In the monograph [28], a partially modified QS was studied using the MathLab Simulinc simulation model development environment (with the SimEvent and StateFlaw libraries, see Pic.1). It is shown that with the help of dynamic priorities, the priority of a non-priority customer is increased once, while the probability of serving these customers increases. However, such a characteristic of QS as the probability of serving the flow of arriving consumers decreases, since non-priority consumers are served longer than priority consumers.

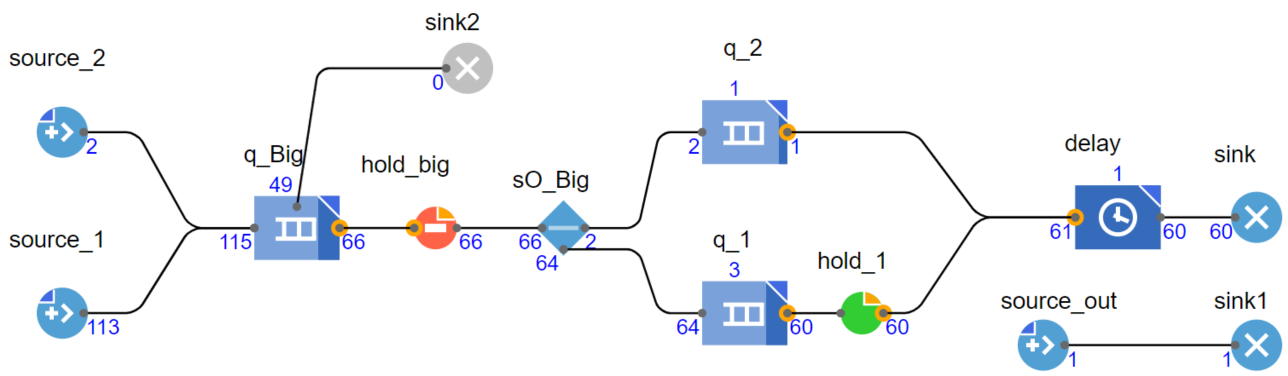

Figure 1 – The main window of the simulation model in the AnyLogic environment
Source: developed by M.Katsman

Taking into account the practical experience of functioning and ensuring the reliability of the railway transport system in extreme conditions of military operations, destruction and restoration of infrastructure, shortage of time and fleet of vehicles, it is proposed to formalize the functioning of this system as a queuing system with priorities, with variable parameters of arrival and servicing the consumers of higher and lower priorities, which allows making more informed decisions for the management of such systems.

The necessity of using, along with analytical methods, simulation modeling tools has been proven, in particular, a simulation model has been developed and implemented, which combines agent and discrete-event simulation principles and allows studying QSs when consumers of different priority are arriving, namely in the part of establishing regularities: probabilities (service, refusal, push-out), time delays (waiting in a queue, under service), queue sizes, order of queue formation when customers of different priority arrive.

The resulting dependencies:

- the probability of servicing higher priority consumers depending on arrival and servicing rates;

- probabilities of servicing lower priority consumers depending on arrival and servicing rates of higher priority consumers;

- probability of "pushing" lower priority consumers out the QS by higher priority consumers, depending on arrival and service intensities of higher priority consumers;

- values of the intensity of service of higher priority consumers μH on the probability PH and the intensity of their arrival λH ;

- values of the probability of PL on the values of the intensity of service μH of the consumers of the highest priority and the duration of the interval tH between these consumers in the arrival flow.

The proposed approach to the study of the consequences of hazardous rail traffic accidents with dangerous goods:

- is the methodological basis for the creation and development of Decision Support System for Task Force leader in the aftermath of such accidents in a single automated control system of railway freight transportation;

- makes it possible to formulate reasonable requirements for the deployment of wreck, recovery and fire teams on the rail network, their equipment and the professional training for team leaders, managers and staff;

- enables to determine the probability and duration of the negative impact of environmentally hazardous transport accidents.

The new multi- and inter- modal transportation planning and management requirements should support innovation in transportation system, its components, their operation and maintenance. They must allow for the smooth integration of new technologies into the system operation domain. Also, the development of new production standards and safety and certification rules by regulators often lag behind technological development, bringing product development to a halt, including new equipment and technologies. Therefore, it is appropriate to include in the service system the possibility of the occurrence of force majeure circumstances and to consider the system with their impact on the results. The proposed theoretical approach consists in the fact that in a multi-component queueing system, the value of the probability of serving a customer in a certain QS component can be determined taking into account that the second component contains the sum of all probabilities of the "enlarged" states of other components of the QS.

Based on this theoretical provision, the modelling of transport maintenance and repair processes, using the example of the repair enterprise, allows to determine the necessary initial parameters of the system components as interacting QSs and to obtain the largest values of the probabilities of servicing the arriving customers in these components and the system as a whole, which provide an acceptable level of its reliability.

When studying real production, logistics, and other systems for which the mathematical apparatus of queueing theory is adequate, the necessary initial mathematical parameters of the system components must be expressed through physical parameters (flows of vehicles or other objects requiring maintenance, performance of equipment for various types of work, production tasks, time constraints, etc.), which will make it possible to optimize specific technologies and enterprises.

When modelling QS processes, non-standard system dynamics solutions were proposed in the AnyLogic University Researcher environment, which allowed to:

- solve a multi-rank system of Kolmogorov equations;
- implement multi-iterative sensitivity experiments with the initial parameters of the QS;
- obtain experimental dependences of the influence of all key parameters on QS indicators, in particular, service probabilities.

The described mathematical apparatus and modelling tools have shown their relevance to real processes and can be applied to improve the performance of multi-component and multiphase queueing systems, which reflect the technological processes occurring in real production, transport-logistics and other systems intended for operation, maintenance and repair of technical equipment of various nature.

The QS model was implemented using System Dynamics computer simulation in the AnyLogic University Researcher environment [29]. The proposed approach to the modelling of maintenance and repair processes in transportation sector by production divisions of the enterprise as a multi-component and multi-phase QS allows to determine the effectiveness of the functioning of such a QS and to obtain arguments for increasing the efficiency of its operation. The graph of the QS states is presented in Fig 2. In Fig. 2 it is indicated:

$\mu_{11} = \mu^{/} + \beta_1^{/}$; $\mu_{12} = 2\mu^{/} + 2\beta_1^{/}$; $\mu_{13} = \mu_{12} + \gamma_1^{/}$; $\mu_{14} = \mu_{12} + 2\gamma_1^{/}$; $\mu_{15} = \mu_{12} + 3\gamma_1^{/}$; $\mu^{/} = 4\mu_1$; $\mu_1 = \frac{1}{\bar{t}_{s_1}}$; $\beta_1^{/} = 4\beta_1$; $\beta_1 = \frac{1}{\bar{t}_{lims_1}}$; $\gamma_1^{/} = 4\gamma_1$; $\gamma_1 = \frac{1}{\bar{t}_{limw_1}}$; $\mu_{21} = \mu^{//} + \beta_2^{//}$; $\mu^{//} = 3\mu_2$; $\mu_2 = \frac{1}{\bar{t}_{s_2}}$; $\beta_2^{//} = 3\beta_2$; $\beta_2 = \frac{1}{\bar{t}_{lims_2}}$; $\mu_{22} = \mu_{21} + \gamma_2^{//}$; $\gamma_2^{//} = 4\gamma_2$; $\gamma_2 = \frac{1}{\bar{t}_{limw_2}}$; where $\bar{t}_{lims_1}$, $\bar{t}_{lims_2}$ are the limited service time; $\bar{t}_{lim_{\dots}}$, $\bar{t}_{lim_{\dots}}$ are the limited waiting time.

The above-mentioned initial parameters reflect and quantitatively characterize both the external conditions of the system's functioning (λ) and its internal capabilities and limitations (μ, β, γ) in response to changes in external conditions, including force majeure circumstances. The simulation model of this two-component QS is presented in Fig. 3. The generalized characteristics of the QS of the system components are the service probabilities Ps/ and Ps//. These characteristics include the initial parameters and some other parameters of the QS components. In the calculation example, the boundary value of the service probabilities of QS components Pb.vs = 0.6 is set, i.e. Ps/ and Ps//must not be less than 0.6 at the same time, provided that the components serve requirements with the same priorities. The results of experiments on the sensitivity of the model are presented in Fig. 4. It can be seen that the determined results of the initial parameters, which correspond to the boundary condition, make it possible to obtain the most acceptable values of the probability values Ps/, Ps//and Ps [29].

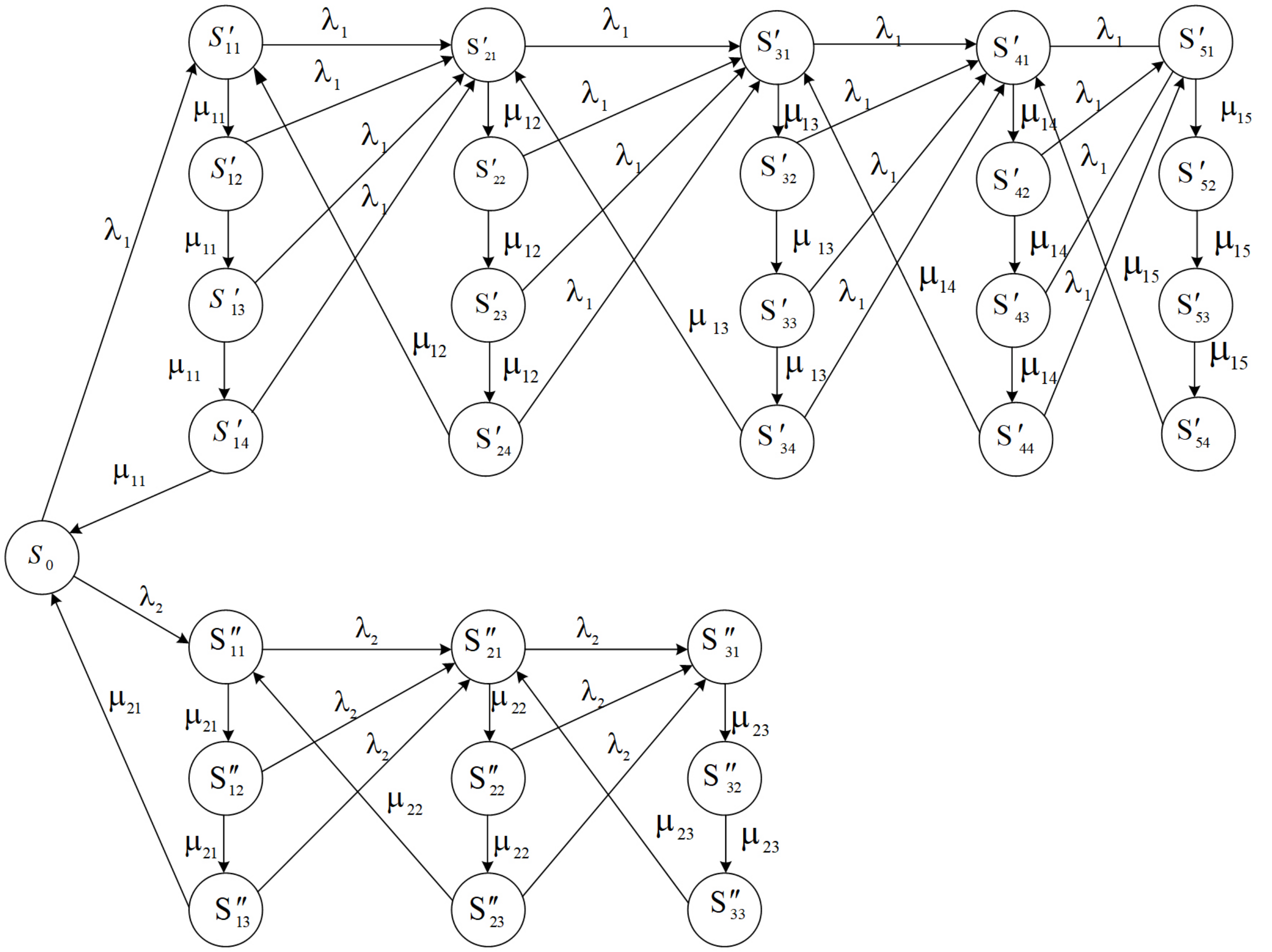

Figure 2 – State graph of QS with restrictions on the time spent in the service period β1,2 and waiting γ1,2

Source: developed by O. Zaporozhets & M.Katsman

New hazards concerning the transportation operation and maintenance of the new equipment and systems should be investigated to complete the safety analysis of new Green Deal Directive outcomes increasing their sustainability in the future. However, the proposed mathematical apparatus must cover new links and allow safe and sustainable solutions.

Strategic safety management of transport systems in the post war period is an effective tool in the process of ensuring sustainable development of the national economy of Ukraine as a whole and the industry in particular [30].

Prospects and ways of integrating Ukrainian metallurgy into the EU steel supply chain. Despite the devastating consequences of the war, the loss of part of its industrial capacity, disruption of logistics and the intensification of competitive pressure on global markets, Ukraine still retains the strategic potential to restore and modernize its metallurgical complex. Moreover, the current situation creates a unique combination of internal and external factors that can not only return the industry to its pre-war level, but also ensure its sustainable competitiveness in accordance with the modern requirements of the green economy.

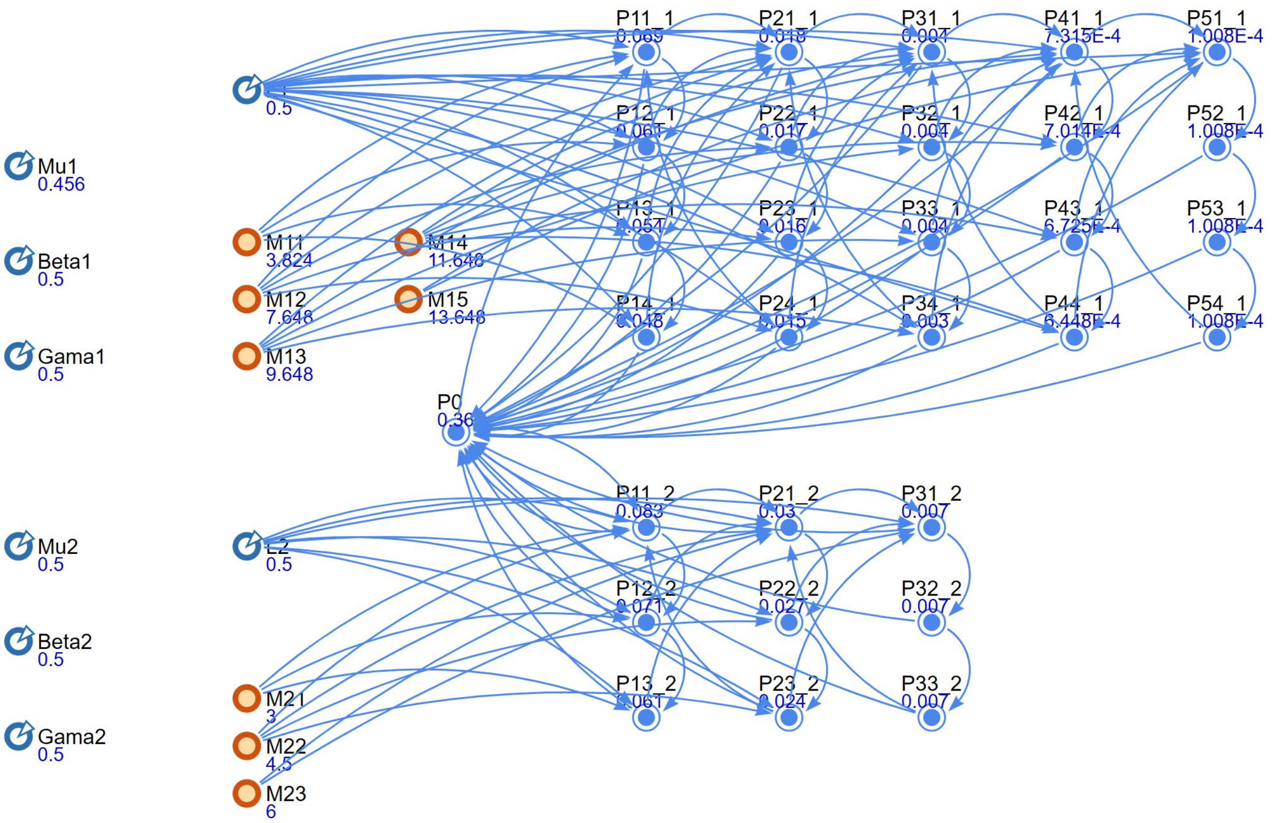

Figure 3 – Probability density of grain delivery time distribution at optimal sizes of the fleet of vehicles (trucks, ships, etc)

Source: developed by O. Zaporozhets & M.Katsman

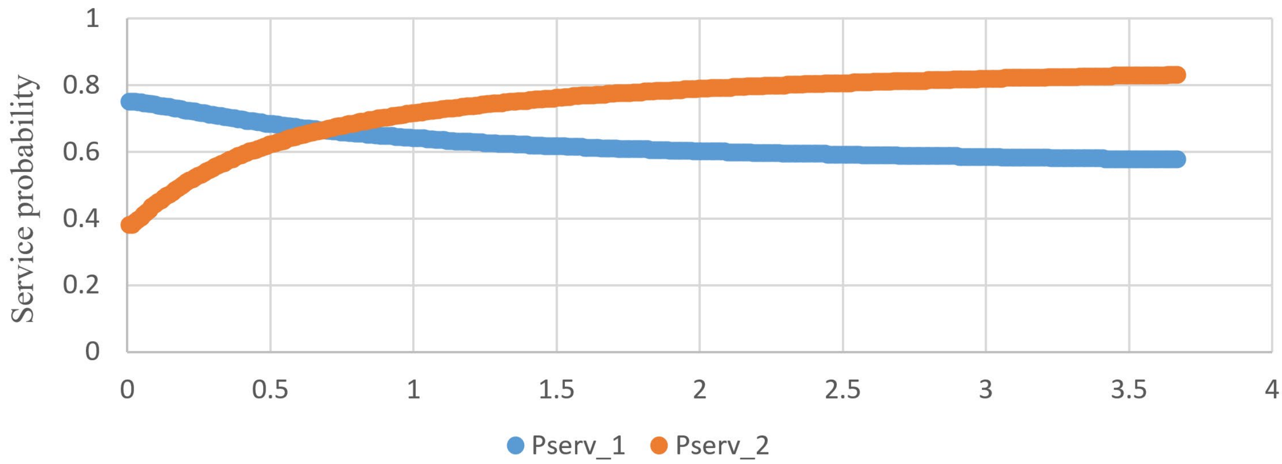

Figure 4. – Graph of the dependence of the probabilities Ps/ and Ps//on the parameter μ/

Source: developed by O. Zaporozhets & M.Katsman

First of all, Ukraine has a powerful resource base - iron ore reserves, which remain one of the largest in Europe. Ukraine has one of the largest reserves of magnetite ores in the world (5 billion tons), suitable for enrichment to an iron content of 68-70%. These products will be in demand in the future as the main raw material for the production of low-carbon steel in electric arc furnaces using DRI. Ukraine will help the global metallurgical industry in its green transition, having the potential to supply 20-25 million tons of DR-quality iron ore raw materials and, thus, satisfying a significant part of the market demand. This is a fundamental factor for the formation of competitive export-oriented metallurgical production. In addition, the country has significant potential for the development of renewable energy, in particular "green" electricity and the hydrogen economy, which are key prerequisites for the creation of low-carbon metallurgical production.

The post-war reconstruction of Ukrainian industry opens a unique "window of opportunity" for the construction of new metallurgical capacities on the principles of climate neutrality, which is due to a complex of economic, technological, political and natural resource factors.

Firstly, a significant part of Ukraine's metallurgical infrastructure has been physically destroyed as a result of military operations, and therefore, the country finds itself faced with the need not to modernize outdated plants, but to actually build new production facilities "from scratch". This significantly simplifies the integration of modern low-carbon technologies, since new construction is technologically and economically more profitable for the implementation of "green" metallurgy standards than the re-equipment of outdated Soviet-style enterprises. This is what is currently being actively implemented by leading countries in the world, in particular Sweden and Germany, building new steelworks based on the principle of using "green" hydrogen and electricity from renewable sources.

Secondly, Ukraine has competitive natural prerequisites for the implementation of low-carbon metallurgical production. In particular, this is access to significant deposits of iron ore, the potential for the production of "green" hydrogen due to the presence of a developed renewable energy sector (wind and solar), as well as geographical proximity to European steel consumption markets. According to European think tanks, Ukraine can play a key role as a supplier of climate-neutral raw materials and products to support the EU's "green" transition within the framework of the European Green Deal.

Third, the post-war recovery is being revived against the backdrop of increased regulatory requirements of the European Union, in particular regarding the carbon footprint of products (CBAM) and the sustainability of supply chains (CDRDD). Therefore, the focus on climate-neutral metallurgy not only corresponds to global environmental trends, but is also a necessary condition for maintaining access of Ukrainian products to the European market.

In addition, the availability of international financial and technological support, including through military reconstruction mechanisms, investment programs and international climate funds, creates a favorable environment for the implementation of such large-scale projects.

Ukrainian metallurgical companies are already planning for this green future. For example, Metinvest is going to build two DRI modules in Ukraine, with an annual capacity of 2.5 million tons each. They supply DRI to the new electric arc complexes of the Zaporizhstal and Kametstal plants. In 2024, Metinvest Group, under difficult war conditions, increased environmental spending and increased its focus on energy efficiency. According to a new report, the company allocated $170 million to environmental protection, which is 2% more than in 2023. Investments in energy efficiency facilities also increased - by more than 50% y/y, to about $17 million. The company continues to develop energy autonomy, in particular, through the installation of gas piston units and plans to launch solar power plants. In 2025, Metinvest began the active phase of the project to thicken enrichment waste at the Severny GOK, which will reduce the load on the tailings. By the end of 2024, 15 Metinvest assets were certified according to the environmental standard ISO 14001:2015, and seven - according to the energy management standard ISO 50001:2011. Thus, the company demonstrates a systematic approach to environmental management and a gradual transition to sustainable production even in wartime conditions. Metinvest is actively preparing for new conditions and transforming its business according to ESG (Environmental, Social, Governance) principles. The EU is introducing new non-financial reporting standards that are radically changing business requirements. Currently, high-quality products are not enough to operate on the European market - they must report on environmental impact, social responsibility and corporate governance.

Ukrainian metallurgical companies are already actively preparing for a green future, focusing on market requirements and global trends in sustainable development. Also, Metinvest Group demonstrates a systematic approach to business transformation in accordance with low-carbon production standards and ESG (Environmental, Social, Governance) principles. The company plans to build two modern direct iron reduction (DRI) modules in Ukraine with an annual capacity of 2.5 million tons each. The DRI products will be produced at new electric arc steelmaking complexes at Zaporizhstal and Kametstal, which will significantly reduce the carbon footprint of steel production.

In the context of war, in 2024 Metinvest continued to increase environmental investments, directing $170 million to environmental protection - this is 2% more than in 2023. Investments in energy efficiency facilities increased significantly, by more than 50% in annual terms, reaching almost $17 million. Among the company's key initiatives is increasing the energy autonomy of enterprises through the installation of gas-piston power plants and the implementation of solar energy projects.

Also in 2025, Metinvest moved into the active phase of implementing the enrichment waste thickening project at the Northern Mining and Processing Complex (GZK), which allows reducing the load on the tailings and improving the environmental performance of the enterprise. At the end of 2024, 15 asset groups were already certified according to the international environmental standard ISO 14001:2015, and seven enterprises - according to the energy management standard ISO 50001:2011, which confirms the systematic approach to environmental management and sustainable production even in wartime.

This approach is quite justified, given the new rules of the game on the European market. In particular, the EU is gradually introducing new standards for non-financial reporting and business sustainability regulation, which radically changes the requirements for suppliers. From now on, to enter the European market, it is not enough to have only high-quality products - companies must transparently report on the environmental and social impact of their activities, adhere to corporate governance standards and meet sustainable development criteria. Therefore, Metinvest's steps to prepare for the new conditions of international trade are not only a forced adaptation to the regulatory environment, but also a strategic investment in the competitiveness of Ukrainian metallurgy in the conditions of post-war reconstruction and transition to a green economy.

ArcelorMittal is also considering the possibility of switching from traditional blast furnace production to electric steelmaking technologies using DRI, as practiced in its European divisions. In particular, outdated coke ovens and a sinter plant were decommissioned in 2022–2023, which allowed to reduce emissions by more than 60,000 tons of CO_2 per year.

Mining and processing company Ferrexpo has set a goal of achieving zero CO_2 emissions (Scope 1+2) by 2050 and investing $3.3 billion in modernization. In 2023, Ferrexpo reduced the carbon intensity of the pellet production process (Scope 1 + 2) by 32% compared to the 2019 baseline. By 2030, the company intends to reduce the carbon intensity of production by 50%. Among the leading projects that will provide the bulk of the carbon reductions, Ferrexpo identified the following: transition to biofuels in the pelletizing process; gradual abandonment of fossil fuels; electrification of technological mining vehicles and equipment; use of hydrogen-powered barges. According to the company's calculations, these measures should provide 90% of the potential emission reduction and are the basis of its Net Zero strategy. At the same time, the first three measures play a leading role - they account for 82% of the emission reduction [32].

Ferrexpo and Metinvest have already established the production of DR pellets, and ArcelorMittal Kryvyi Rih was preparing a pellet plant with a capacity of 5 million tons per year (the project was suspended due to the war, but with high potential for recovery). The Canadian company Black Iron planned to produce high-quality concentrate (4–8 million tons per year), the project was suspended, but has great prospects after the war gmk.center. According to GMK Center, Ukraine can become a key player in the European DRI/HBI market, with a potential of 20–25 million tons, which corresponds to approximately 14% of global demand.

Thus, Ukrainian metallurgical giants - Metinvest, ArcelorMittal Kryvyi Rih, Ferrexpo, Interpipe - are already implementing, albeit different, but complementary initiatives to transition to low-carbon technologies. This includes DRI modules, electric steelmaking, fuel decarbonization, construction of pellet plants and hydrogen projects. These steps demonstrate a systematic approach to a true green transformation of the national metallurgy and create a foundation for integration into the EU's "green" supply chains.

According to GMK center estimates, the total capital expenditures required to implement the already announced "green" metallurgy projects in Ukraine are about $11 billion. These projects will be implemented only on condition that Ukrainian companies receive access to European "green" financing instruments, similar to those received by European companies. Thanks to this support Ukrainian metallurgy can become an important part of the European low-carbon supply chain, which will be beneficial for all stakeholders, and especially for European metallurgy.

Conclusions. The analysis of current trends and strategic factors in the development of sustainable supply chains of metallurgical products from Ukraine to the European Union allows us to draw a number of important conclusions. First, Ukraine's unique geographical location creates competitive advantages for integration into European supply chains. Proximity to key EU markets, convenient access to Black Sea ports, and active participation in projects to develop transport and logistics infrastructure contribute to reducing transportation costs and the carbon footprint of supplies. This, in turn, increases the attractiveness of Ukrainian metallurgical products for European partners, who are increasingly focused on environmental performance and supply chain efficiency. Second, the political factor plays a key role in creating a favorable environment for the development of sustainable supply chains. The status of a candidate country for accession to the EU opens up for Ukraine the possibility of deeper economic integration, which includes the harmonization of environmental and social standards, access to financing within the framework of European reconstruction programs, as well as the attraction of modern technologies and investments for the modernization of the industry. This creates a foundation for increasing the competitiveness of the Ukrainian metallurgy in the European market.Thirdly, the strategic transition of the EU economy on the basis of the European Green Deal forms a long-term and stable demand for climate-neutral raw materials and products. In particular, the demand for steel with a low carbon footprint, the production of which is possible due to the use of DRI technologies, green hydrogen and renewable energy, opens up a unique "window of opportunity" for Ukraine. Under the conditions of proper modernization of production facilities, development of logistics infrastructure and compliance with modern environmental standards, Ukraine is able to become an important element of European green supply chains. Thus, a complex combination of geographical, political and economic factors, as well as the desire to restore and decarbonize the national metallurgy, creates the prerequisites for the active integration of Ukraine into sustainable EU supply chains, which, in turn, will contribute not only to the development of Ukrainian metallurgy, but also to the overall post-war economic reconstruction of the country. The development of sustainable supply chains of metallurgical products from Ukraine to the European Union is not only a strategic condition for economic integration, but also a key factor in increasing the competitiveness of Ukrainian metallurgy in the post-war period. At the same time, it is the logistics component that plays a decisive role in the formation of effective and sustainable supply channels that can meet the modern requirements of the EU market and regulatory environment. Today, the Ukrainian metallurgical industry faces significant logistical challenges: a limited number of transport corridors, overloaded border crossings, high transportation costs, difficult coordination between different modes of transport, and insufficient digitalization of logistics processes. These factors not only reduce the reliability and predictability of supplies, but also increase the carbon footprint of products due to inefficient use of transport infrastructure. At the same time, the development of sustainable logistics solutions - diversification of transport routes, modernization of railway and port infrastructure, transition to multimodal environmentally friendly transportation, digitalization of supply chains - is a necessary condition for the integration of Ukraine into the green supply chains of the EU. It is the optimization of logistics that will allow to reduce the time and costs of transportation, reduce greenhouse gas emissions at the delivery stage and increase the overall transparency and compliance of supplies with modern environmental standards, which is becoming increasingly relevant in the context of the implementation of such European initiatives as the Green Deal, CBAM and CDRDD. These factors create a unique "window of opportunity" for the integration of Ukrainian metallurgy into the green supply chains of the European Union. The essence of these chains is not only to reduce the carbon footprint of finished products, but also to comply with high standards of transparency, social responsibility and environmental safety at all stages - from raw material extraction to delivery to the end consumer. The results of the study show that the digitalization of metallurgical supply chains is a critical prerequisite for Ukraine's integration into sustainable EU supply chains. In the context of new EU regulatory requirements, such as the CDRDD and Ecodesign Regulation, without an adequate level of digital transparency, Ukrainian manufacturers will not be able to ensure the necessary level of traceability, environmental responsibility and the formation of digital product passports. To do this, Ukraine needs to systematically develop unified digital platforms for supply chain participants, integrate information systems in accordance with European standards, invest in digital infrastructure and stimulate business to implement modern IT solutions. Without such measures, the creation of sustainable, transparent and competitive supply chains of metallurgical products from Ukraine to the EU will remain a difficult task, which will hinder the country's post-war economic reconstruction and integration into the European market.In Ukraine, environmental protection is being done in accordance with state requirements at the moment. Its improvement is possible due to step-by-step implementation of the European rules and principles including the Green Deal portfolio. Thus, with the right policy, state support, and cooperation with European partners, Ukraine has a real chance to make a strategic "leap" into the future, transforming the metallurgical industry from a post-conflict vulnerable sector into one of the drivers of economic recovery and an important component of Europe's green transformation.

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