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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

**GREEN SUPPLY CHAIN MANAGEMENT: THE CASE OF
GANJA ALUMINUM COMPLEX**

Specialization: 5308.01 – “General Economy”

Field of Science: Economic Sciences

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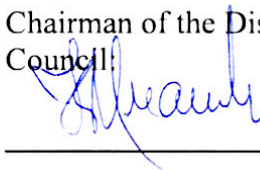
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GENERAL CHARACTERISTICS OF THE RESEARCH

Relevance of the Research Topic and Degree of Development: Supply chain management encompasses a broad range of stages, beginning with the provision of primary production inputs and extending to the delivery of finished goods to final consumers. In the contemporary era, the emergence of environmental challenges—particularly global climate change—has necessitated a transition toward green standards within supply chain management systems. Consequently, Green Supply Chain Management (GSCM) has emerged as a significant scientific concept.

An examination of Azerbaijan’s political and economic strategies aimed at building a sustainable future—particularly its strategic roadmaps—reveals that the scientific investigation of the aluminum industry, which holds substantial eco-economic weight, is highly relevant. This dissertation has been prepared in alignment with the Decree of the President of the Republic of Azerbaijan entitled “Azerbaijan 2030: National Priorities for Socio-Economic Development,” the United Nations Sustainable Development Goals (SDGs – 7, 8, 9, 12, 13), and the green strategies advanced within the framework of COP29. The presented research is not only timely but also possesses considerable theoretical and practical significance for the sustainable development of the country, evaluated from a global perspective and contextualized within the regional dimension.

The concept of the green economy has evolved through an eco-economic critique of classical and traditional economic paradigms. In this regard, a transition toward a green economy requires a comprehensive understanding of economic theory, including macroeconomics, microeconomics, economic regulation, development processes, and structural challenges. Within this broad scientific platform, Azerbaijani economists such as N.M. Imanov, Sh.M. Muradov, M.A. Ahmadov, A.X. Nuriyev, F.F. Mustafayev, R.P. Sultanova, A.A. Aliyev, E.Y. Mammadov, S.A. Shabanov, and others have produced valuable foundational works and conducted numerous studies contributing to the theoretical basis of economic science.

The issue of greening the economy, the formation and improvement of green management strategies, and the development of new methods and optimal models for sustainable development have been widely explored in global academic research. Among national scholars, V.A. Gasimli, M.G. Gulaliyev, I.Z. Seyfullayev, F.C. Hasanov, Sh.Z. Mukhtarov, and others have made notable contributions to research in green economy and sustainable development.

GSCM constitutes an essential strategic component of the green economy. As this field remains relatively new within the scientific sphere, the number of researchers globally focusing specifically on this topic is still limited. International scholars such as J. Sarkis, Y. Dou, C. Achillas, K. Lyons, T. Paksoy, G. Shi, G. Zanghelini, and others have produced scholarly works addressing the fundamental principles, stages, strategies, and general eco-economic analyses of green supply chain management.

The Ganja Aluminum Complex (GAC), the region's principal aluminum producer, accounts for more than 5% of Azerbaijan's non-oil export value. In addition to examining the green economic analysis and sustainability of Azerbaijan's aluminum industry, this dissertation also investigates its current economic condition, overall development trajectory, structural challenges, technological system, and future strategic objectives.

The global significance of GSCM for ensuring sustainable economic development and a sustainable future is becoming increasingly evident. The integration of industrial sectors into green design models in accordance with evolving business requirements has become an imperative necessity. In order to minimize carbon emissions by 2050, global political and economic organizations and alliances are demanding that businesses fulfill green commitments in line with internationally agreed frameworks and climate targets. Approximately 3% of global carbon emissions resulting directly from industrial activities are attributed solely to the aluminum sector. Given the magnitude of this figure, the issue has become a central concern for aluminum producers worldwide. For Azerbaijan, which

is rapidly integrating into the international political-economic arena and global business environment through green strategies, the study of this topic within the context of its strategic aluminum industry holds critical importance.

Object of the Research: The object of the research is the Ganja Aluminum Complex (GAC).

Subject of research: The features of the integration and application of the green supply chain management system in the Azerbaijani aluminum industry, as well as the analysis of the essence and development trends of eco-economic relations formed as a result of these processes.

Purpose and Objectives of the Research: An examination of the global economic landscape of the modern world reveals an undeniable reality: the rapid expansion of green economic principles. Today, the economic sustainability of business entities that fail to understand the essence of the green supply chain system and operate in accordance with its principles is increasingly called into question.

The primary aim of this dissertation is to develop new economic, environmental, and managerial proposals based on a comprehensive examination of GSCM processes—ranging from theoretical foundations to practical applications, from specific features to future prospects, and from traditional challenges to transformative technological solutions.

To achieve this strategically significant objective, the following tasks have been set:

- To synthesize the interrelationship between the current trajectory of the global economy and the realities of global climate change;
- To classify theoretical approaches to GSCM;
- To identify the key stages of the GSCM system;
- To describe the current state and overall eco-economic indicators of the global aluminum industry;
- To examine the present role and development prospects of the aluminum industry within the national economy;
- To analyze the current condition, development trends, and overall potential of Azerbaijan's green energy sector;

- To determine the organization of the principal stages of the GSCM system within the aluminum industry context, using GAC as a case study;
- To identify green strategies applicable to the aluminum industry;
- To study the primary aluminum production process and analyze its eco-economic indicators;
- To investigate innovative technologies related to the greening of the aluminum industry.

Research Methods: In the preparation of the dissertation, a wide range of research methods were employed, including scientific abstraction, theoretical analysis, systematic analysis, synthesis, deduction, induction, practical observation, comparative analysis, technological analysis, econometric modeling, laboratory analysis, empirical methods, and other relevant methodologies.

Main Provisions Submitted for Defense: The principal propositions submitted for academic defense are as follows:

- The systematic implementation of GSCM across its stages holds fundamental importance for resolving environmental challenges and ensuring the sustainable management of supply chains.
- In the aluminum industry—where global demand continues to grow steadily—the reduction of carbon emissions constitutes a crucial factor for ecological sustainability within this strategic sector.
- Within the framework of modern business requirements, assessing the environmental and economic impacts of Azerbaijan’s aluminum industry represents a key strategic criterion in global competition.
- Simulation modeling in GSCM enhances the deepening and forecasting of complex system relationships.
- The implementation of new organizational structures, strategies, and innovative technologies within GSCM in the aluminum industry can increase eco-economic efficiency in aluminum production in the long term.

Scientific Novelty of the Research: The scientific contributions of the dissertation include:

- Conducting, for the first time, a scientific study of Azerbaijan's aluminum industry from a green economic perspective, alongside a comprehensive systematic analysis of GSCM.
- Performing a mathematical forecast of CO₂ emissions from the global aluminum industrial chain up to 2030 through the application of the ARIMA model.
- Presenting, for the first time, a green production passport for the Ganja Aluminum Complex.
- Conducting a prospective eco-economic assessment of inert anode technology.
- Implementing a simulation model within the GSCM system.

Theoretical and Practical Significance of the Research: The theoretical and practical significance of the research lies in the eco-economic assessment of the aluminum industry, which holds strategic importance for the national economy, and in highlighting green principles as a central criterion for ensuring a sustainable future.

Information Base of the Research: Another distinctive feature of the research is the evaluation of GSCM through a specific strategic sector—the aluminum industry. The scientific analysis of both strategic domains requires extensive and diverse information and statistical data from multiple spheres, as well as substantial practical experience, since the research is conducted directly within an industrial complex context.

Statistical data related to the green economy were obtained from the databases of the United Nations, the World Bank, and the European Union, as well as from sustainable development projects and research-information centers focusing on global energy consumption and carbon emissions.

Data concerning the aluminum industry were collected from the International Aluminium Institute and the Aluminum Association major global aluminum companies, the London Metal Exchange, and other relevant institutions.

Information related to Azerbaijan was sourced from official

platforms, including the State Statistical Committee of the Republic of Azerbaijan, the Ministry of Energy, the State Agency for Renewable Energy Sources under the Ministry of Energy, the Center for Analysis of Economic Reforms and Communication, Azerbaijan Industrial Corporation, and other official institutions.

Approbation and Implementation of the Dissertation: The findings, general and specific provisions, identified problems, and substantiated proposals and recommendations of the dissertation have been reflected in 18 published articles and conference papers in domestic and international journals and proceedings. Of these, six (including four indexed in Scopus) were published in international abstracting and indexing systems recommended by the Higher Attestation Commission. International publications appeared in reputable journals in the United States, Malaysia, the Czech Republic, and Türkiye.

Research results were presented at six international conferences, two of which were held abroad, with corresponding articles and abstracts published in the conference proceedings.

The total volume of the dissertation in characters, with the volume of its structural sections separately noted. The logical foundations of the research work are determined by the subject of the research topic, its object, and its aims and objectives. The dissertation consists of an introduction (12765 characters), three chapters (Chapter I – 41452 characters, Chapter II – 56988 characters, III Chapter – 87,849 characters), the conclusions (10,726 characters), the list of sources and 219 references, - appendices and a list of abbreviations and symbols. The dissertation – comprising 163 pages (209,780 characters, excluding tables, graphs and the bibliography) – contains 12 graphs, 18 tables and 19 figures, in accordance with the logic and substance of the work.

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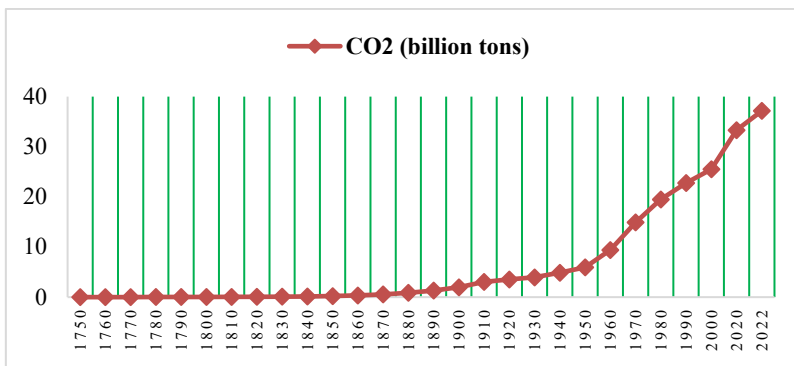
List of Abbreviations and Symbols

SUMMARY OF THE RESEARCH WORK

In the introduction of the dissertation, the relevance of the topic, the state of research on the problem, the research objectives and tasks, the object and subject of the study, the main propositions, scientific novelty, practical significance, and approbation are presented.

Chapter I of the dissertation, entitled “Theoretical Foundations of Green Supply Chain Management and the Organization of the Aluminium Industry,” consists of three paragraphs. The first paragraph, titled “The Essence of the Transition to a Green Supply System,” examines the philosophical foundations of Green Supply Chain Management (GSCM) as a new concept and explains the driving forces behind the transformation from a traditional supply chain to a green one.

Today, the transition toward comprehensive research on the green economy and sustainable development has become an imperative in determining the future trajectory of the world. Figure 1 visually illustrates the historical evolution of the global industrial chain and its impact on the environment.



Graph 1. Global anthropogenic carbon dioxide emissions (in billion tons) since the industrial revolution

Source: Prepared by the author based on data from Friedlingstein¹

¹ Global Carbon Budget Data [Electronic resource] / Global Carbon Project, - 2022. – URL: <https://www.globalcarbonproject.org/carbonbudget/22/data.htm>

The collision of the traditional supply chain system with escalating environmental challenges led to the emergence of the new concept of Green Supply Chain Management (GSCM). Traditional supply chain management focuses on processes ranging from raw material procurement to the final consumer and primarily aims at economic efficiency, while largely disregarding environmental impacts. In contrast, Green Supply Chain Management is grounded in the principles of environmental sustainability and encompasses strategic approaches such as green product manufacturing, energy efficiency, waste reduction, and environmentally compliant transportation management.

The second paragraph, entitled “The Main Stages of Green Supply Chain Management,” provides a substantiated analysis of GSCM principles and offers theoretical justifications, particularly regarding the classification of its core stages.

It has been observed that when projects designed in accordance with GSCM strategies are successfully implemented, companies seeking active participation in the global business environment achieve increased product sales, enhanced efficiency, and higher overall economic profitability as a result of compliance with environmental standards. GSCM has emerged as a key strategy that can provide competitive advantages in the business environment along with the profits needed for companies' profits.²

GSCM has emerged as a key strategic approach capable of generating the necessary gains for corporate profitability while simultaneously providing competitive advantages in the business environment. It serves as an effective instrument aimed at reducing business costs and increasing revenues:

GSCM = Cost Reduction + Efficiency and Profit Growth

Procurement, as the initial stage of the supply chain system, holds substantial importance, serving as a fundamental direction of business

² Fang C. & Zhang J. / Performance of green supply chain management: A systematic review and meta analysis. *Journal of Cleaner Production* – 2018. Volume 183, 1064–1081. doi:10.1016/j.jclepro.2018.02.171

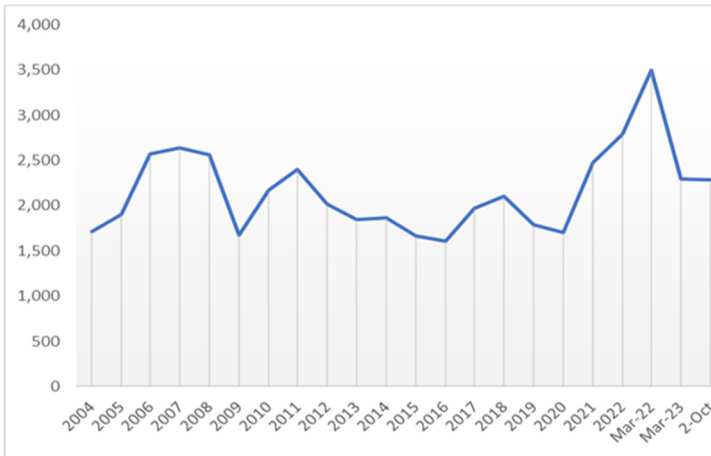
strategy and carrying significant weight in overall value creation. The primary objective of green procurement (GP) is not only to ensure compliance with environmental regulations but also to reduce product acquisition costs.

Green production (GPr) represents a stage of GSCM that seeks to minimize, to the greatest possible extent, all potential negative impacts on ecology and climate within the production system. At this stage, raw materials enter the system and, through environmentally compliant processing, are transformed into finished goods before exiting the system.

Green transportation (GT) refers to the stage in which transportation methods based on renewable energy sources are utilized, characterized by minimal or zero greenhouse gas emissions and negligible environmental impact. For heavy cargo transportation, rail and water transport remain environmentally and economically unparalleled alternatives within the green transportation system. Railways account for only 0.2% of the global emissions burden. Moreover, trains possess significant economic advantages over trucks, offering a far more cost-efficient mode of freight transport. Thus, up to 9 times less energy is consumed in rail transportation.³

The 3rd paragraph of Chapter I of the dissertation is titled “Current Status of the Global Aluminum Industry and Forecasting Carbon Dioxide Emissions Using the ARIMA Model.” Here, the macroeconomic picture of the world aluminum industry, major producers, consumption growth dynamics, and econometric forecasting of the amount of carbon emissions by industry were carried out. Graph 2 depicts the increasing value of aluminum in the world.

³ Train vs. Truck Shipping: Pros and Cons [Infographic] [Electronic resource] / Freightera freight marketplace corporate web, June 2019. - URL: <https://www.freightera.com/blog/train-vs-truck-transportation-efficiency-cost-advantages-disadvantages-infographic/>

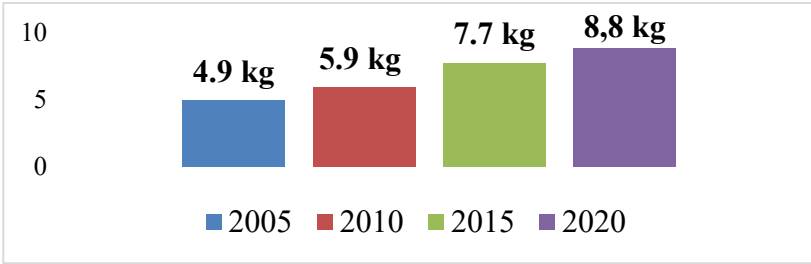


Graph 2. World market prices of 1 ton of aluminum (in US dollars)
Source: Compiled by the author based on data from the London Metal Exchange⁴

In 2022, global aluminium production reached 69 million tons, of which 40 million tons were produced by China alone. Aluminium prices have consistently experienced volatility in commodity exchanges. For the first time in the past 20 years, the price of one ton of aluminium exceeded the threshold of USD 3,500 in 2022, followed by a gradual decline.

The growing economic demand for aluminium can be observed through the dynamics of per capita consumption, which demonstrates a rapidly increasing global trend year by year. At the same time, carbon emissions originating from the aluminium industrial value chain are significantly high. Therefore, it is essential to quantify these emissions and conduct reliable econometric forecasts to assess their future trajectory.

⁴ LME Aluminium [Electronic resource] / London Metal Exchange (LME) official website. 23 sep. 2024.– URL: <https://www.lme.com/Metals/Non-ferrous/LME-Aluminium#Price+graphs>



Graph 3. Per capita consumption dynamics of aluminum

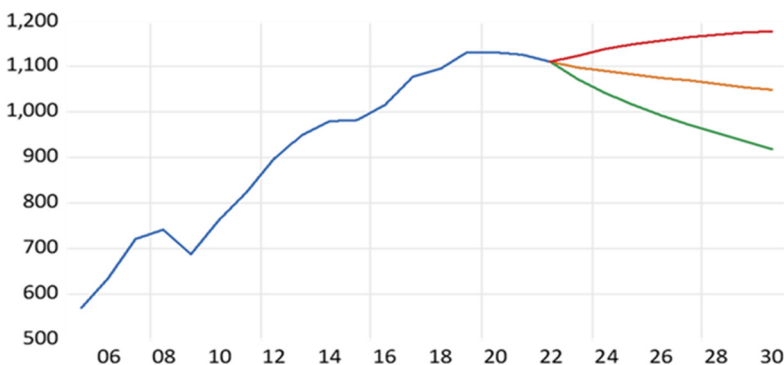
Source: Compiled by the author based on Aluminas statistics

In the research, the ARIMA model was applied to forecast mathematically the trajectory of CO₂ emissions released into the atmosphere by the aluminium industry up to 2030, based on the overall trend observed over the past decades. Table 1 presents the unit root test results for the 17-year time series of aluminium-related emissions. The absence of stationarity at the initial level necessitated the application of the ARIMA model.

**Table 1.
Unit root test**

ADF		Level	1 st dif.	2 nd dif.
Trend and intercept	t-statistics	-1.07	-3.26	-4.71
	p-value	0.90	0.10	0.01
Phillips-Perron		Level	1 st dif.	2 nd dif.
Trend and intercept	t-statistics	-1.30	-3.28	-6.58
	p-value	0.84	0.10	0.00

Figure 4 presents the overall data on ACE (Aluminium Carbon Emissions). In the graph, the green and red lines indicate the uncertainty bounds, while the blue line represents the actual emissions and the orange line illustrates the forecasted emissions.



Graph 4. Current status and future forecast of carbon emissions in the global aluminum industry using the ARIMA model (million tons)

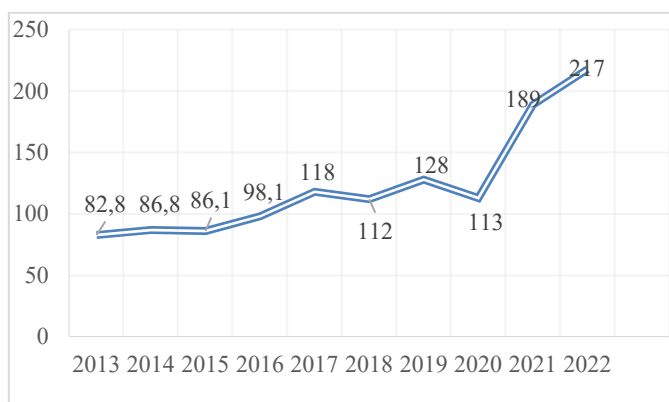
Source: Compiled by the author in Eviews software

Within the existing historical time frame, the volume of CO₂ emissions exhibited a consistent upward trajectory until 2022, reflecting the heavy environmental burden of industrial activity. However, in the period following 2020, a certain decline was observed due to stricter environmental regulations and the broader application of technological advancements. According to the mathematical forecast obtained through the application of the ARIMA model, if the current trajectory continues in line with prevailing trends, a 6% reduction in CO₂ emissions is expected by 2030 compared to the level observed in 2022, even in the context of increasing annual production and consumption.

Chapter II of the dissertation, entitled “Development Prospects of the Aluminium Industry and the Renewable Energy Sector in Azerbaijan,” consists of three paragraphs. The first subsection of this chapter, “The Formation of the Modern Aluminium Industry in Azerbaijan and Its Role in the National Economy,” examines the establishment, current state, and future growth-oriented objectives of Azerbaijan’s aluminium industry, which holds strategic importance and a significant share within the country’s non-oil sector.

The foundation of the modern aluminium industry in Azerbaijan was laid in March 2008 with the establishment of a new aluminium complex in Ganja, possessing an annual production

capacity of 50–55 thousand tons, inaugurated with the participation of the President of the Republic of Azerbaijan, Mr. Ilham Aliyev. According to statistics released by the Center for Analysis of Economic Reforms and Communication (CAERC), Azerbaijan’s total exports amounted to USD 38 billion in 2022, of which USD 3 billion accounted for the non-oil sector.⁵ One of the positive trends in the non-oil sector is the rapid growth observed in the aluminium industry. According to the Center for Economic and Industrial Research (CEIC), Azerbaijan’s total aluminium exports amounted to USD 116 million in 2020, rising to USD 190 million in 2021.

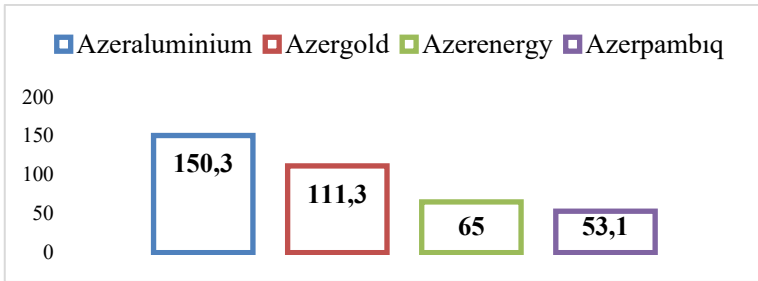


Graph 5. Azerbaijan's aluminum exports (in million US\$)

Source: Compiled by the author based on the CEIC database

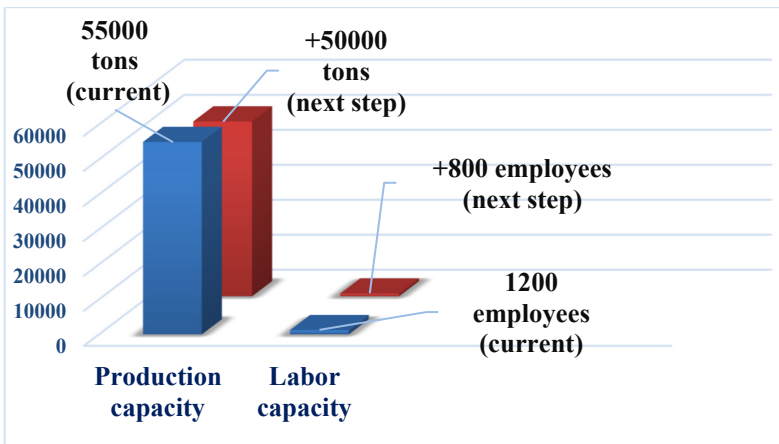
GAC, owned by Azeraluminium, the leading force in the aluminum industry in Azerbaijan, is the main site for aluminum production in the country. Azeraluminium is a significant player in the non-oil sector of Azerbaijan and plays a key role in aluminum exports across the country. Charts 6 and 7 illustrate a number of key indicators for Azeraluminium.

⁵ Azərbaycan Respublikası İqtisadi İslahatların Təhlili və Kommunikasiya Mərkəzinin rəsmi saytı. – 09 yanvar, - 2023. - URL: <https://ereforms.gov.az/az/media/xeberler/2022-ci-ilde-qeyri-neft-ixraci-3-milyard-abs-dollar-olub-557>



Graph 6. Ranking of the main state-owned exporting companies in the non-oil sector in January-December 2022

Source: It was compiled by the author on the basis of CACER data



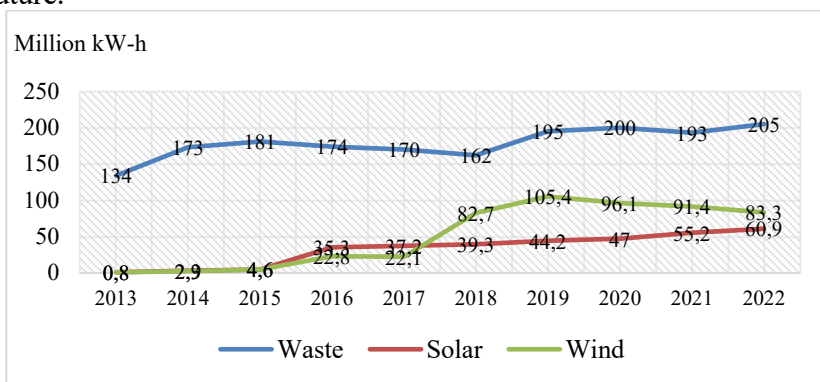
Graph 7. Targeted production and workforce at GAC for the current and next phase

Source: It was compiled by the author on the basis of CACER data

“In the second paragraph of Chapter II, entitled “Assessment of Azerbaijan’s Alternative Energy Sector, Its Potential, and Energy Policy,” the energy sector—on which the aluminium industry is directly dependent—was analyzed, with particular emphasis on Azerbaijan’s green energy resources and the existing potential to support the future needs of heavy industrial sectors.

The development of the aluminium industry is highly dependent on energy supply. Given the industry’s high energy consumption and

the correspondingly large volume of CO₂ emissions, ensuring its operation with green energy represents one of the most pressing global challenges. According to data from the State Statistical Committee of the Republic of Azerbaijan (SSCRA), total electricity production in Azerbaijan in 2022 amounted to 29,004.3 million kWh, of which 27,059.1 million kWh was generated by thermal power plants (TPPs), 1,595.7 million kWh by hydropower plants (HPPs), and 349.5 million kWh from other renewable energy sources.⁶ Azerbaijan possesses significant potential in renewable energy sources, and active efforts have been made over the past decade to harness this potential. Furthermore, even larger projects in this field are planned for the near future.



Graph 8. Types of green energy formed in Azerbaijan in the last 10 years and the amount of annual energy production

Source: Compiled by the author based on SSCRA data

Renewable energy is one of the most fundamental requirements of a GSCM system, and the Azerbaijani government has been implementing substantial projects to meet the industry’s energy demand through green alternatives. A notable example is the solar power plant project, with a capacity of 230 MW, developed in cooperation with Masdar (UAE) on April 6, 2021.

⁶ Energetika. Energetika sektoru üzrə əsas makroiqtisadi və enerji səmərəliliyi göstəriciləri. Ümumi enerji təchizatında enerji növlərindən istifadə [Elektron resurs] // Azərbaycan Respublikasının Dövlət Statistika Komitəsi. – 2022, 2023. – URL: https://www.stat.gov.az/source/balance_fuel/

Azerbaijan's renewable energy potential exceeds 1,300 MW, which corresponds to an annual electricity generation of approximately 11,400 GWh. On average, for an annual aluminium production of 50,000 tons, the daily energy consumption amounts to 2 million kWh, while the annual consumption is 730 GWh. This energy usage represents only 6–7% of the country's current renewable energy potential. In other words, Azerbaijan's existing renewable energy resources are sufficient to fully support aluminium production and can easily accommodate additional energy demand.

The third paragraph of Chapter II, entitled “Key Product Markets for Aluminium and Green Marketing,” analyzes the major end-use markets for aluminium—including automotive, aviation, aerospace, and construction industries—in accordance with green marketing principles. Another critical aspect of the GSCM system is the product sales process. In the highly competitive global aluminium industry, selling environmentally compliant and economically viable brands to appropriate markets is of paramount importance. For instance, in Azerbaijan, the regular supply of environmentally certified aluminium rolls and sheets—such as grades 1050, 3003, 3105, 8011, as well as the planned 5-series products intended for high-demand markets like the United States—to suitable business facilities constitutes one of the core business strategies for sustainable growth in the aluminium industry and the non-oil sector's export potential.

Chapter III of the dissertation, entitled “Application Methods of Green Passport, Simulation Modeling, Structural Design, and Sustainable Technologies at the Ganja Aluminium Complex,” also consists of three paragraphs. The first paragraph, “Stage-by-Stage Analysis of Green Supply Chain Management at the Ganja Aluminium Complex,” examines the green procurement, production, and transportation processes, analyzing all relevant GSCM stages from initial raw material supply to final transportation. Particular emphasis was placed on the development of a green production passport.

The main strategic raw materials for primary aluminium production are:

- Aluminium oxide
- Anode carbon blocks

- Cryolite

These raw materials constitute the primary financial components circulating within the aluminium industry, with procurement serving as a key operational point. The production facility prioritizes revenue allocation to raw material supply to ensure the continuity of the process. At the Ganja Aluminium Complex, the strategic vector for integrating green economic principles into the GSCM system is the implementation of an overall planning process.

Successful management in the green procurement (GP) stage can be summarized through five core elements: Quality (Q), Quantity (Q'), Price (P), Time (T), and Location (L). Proper and effective application of these elements forms the foundation of efficient GP management. The consolidation of these five indicators into a single strategic platform can be classified as the GP Pentagon Model (Figure 1). The central principle of the Pentagon Model is to define an optimal strategy that balances the minimum and maximum values selected for each direction.

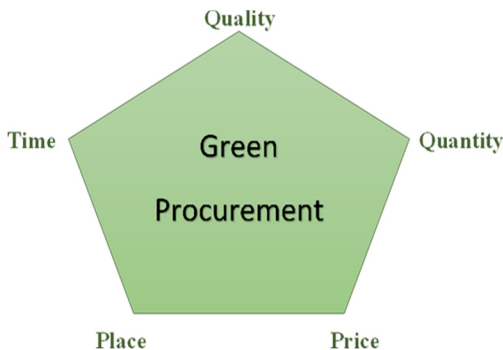


Figure 1. Pentagon model for effective GP management

Source: Compiled by the author

The principle can be applied mathematically using the following formulas:

- $GP = \max(K_1, K_2, K_3, \dots, K_n)$
- $GP = \max(K'_1, K'_2, K'_3, \dots, K'_n)$
- $GP = \min(Q_1, Q_2, Q_3, \dots, Q_n)$
- $GP = \min(M_1, M_2, M_3, \dots, M_n)$
- $GP = \min(T_1, T_2, T_3, \dots, T_n)$

In a GSCM system, specific methods and techniques must be applied to analyze companies' eco-economic indicators. To obtain reliable statistical results, such research requires direct, practical observation of operational management processes within the company.

Table 2.
Procurement information on the main raw materials in GAC

Name of product	Price	Country of import
1. Aluminum oxide	480\$	Guinea, Jamaica
2. Carbon anode blocks	1550\$	China, Turkiye
3. Aluminum fluoride	980\$	Russia, Belarus
4. Cryolite	1750\$	China

Source: Prepared by the author

Approximately 90% of the total CO₂ emissions in the aluminium industry occur during this process (Figure 2). At the Ganja Aluminium Complex (GAC), this process is carried out across two electrolysis plants.

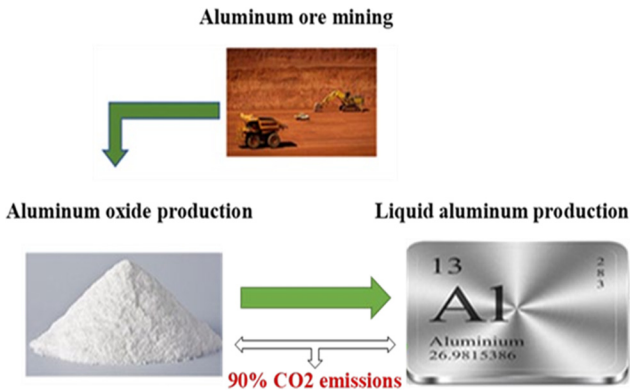


Figure 2. Aluminum production processes and the stage with the most carbon dioxide emissions

Source: Prepared by the author

Globally, the production of one ton of primary aluminium results in approximately 16.6 tons of CO₂ emissions, both direct and indirect,

released into the atmosphere. Table 3 presents the amount of CO₂ emitted per ton of aluminium across all stages of the production supply chain. Since aluminium production involves high energy consumption, it is essential from a green standards perspective to identify the energy sources used. Table 4 illustrates this sequence of energy resource utilization.

Table 3.
The amount of carbon emissions released by production stages (in tons)

	Electrolysis (indirect)	Perfluoro-carbon (direct)	Manufacturing process (direct)	Ancillary materials	Thermal energy	Transport
Mining	0.01	*	*	*	0.04	*
Refinement	0.4	*	*	0.4	1.6	0.2
Anode production	*	*	0.1	0.7	0.1	*
Electrolysis	10.3	0.8	1.5	0.1	*	0.2
Casting	*	*	*	*	0.1	*
Primary aluminium	10.7	0.8	1.7	1.2	1.8	0.4

Source: Compiled by the author based on the statistics of the International Aluminum Institute⁷

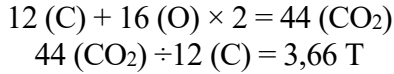
Table 4.
The amount of CO₂ produced by the production of 1 ton of aluminum according to different energy sources.

Coal	15-20 T CO ₂
Petroleum	10-15 T CO ₂
Natural gas	6-10 T CO ₂
Other renewables	0-2 T CO ₂

Source: Prepared by the author

⁷ IAI. Primary Aluminium Production. London: International Aluminium Institute official website. – 2023. – URL: <https://international-aluminium.org/statistics/primary-aluminium-production/>

At the Ganja Aluminium Complex (GAC), the production of one ton of aluminium requires 0.408 metric tons of anodes. Based on this, it is determined that the consumption of 1 ton of anodes generates 3.66 tons of CO₂:



According to the equation, 12 moles of carbon (C) react with 32 moles of oxygen (O₂) to produce 44 moles of CO₂. The molar ratio between CO₂ and C during the technological process is obtained by dividing 44 moles of CO₂ by 12 moles of C, resulting in a factor of 3.66. Considering the net anode consumption of 0.408 tons, the calculated outcome of the study shows that the atmospheric CO₂ emissions per ton of aluminium produced in Azerbaijan are 1.49 tons:

$$\text{CO}_2 = 0.408 \times 3.66 = 1.49 \text{ TCO}_2 = 0.408 \times 3.66 = 1.49 \text{ T}$$

In 2022, the GAC's annual production amounted to 53,000 tons of primary aluminium, which corresponds to an average daily output of approximately 145 tons. Based on these figures, the energy consumption per ton of aluminium can be determined using the following formula:

$$E = \frac{E_g}{\dot{I}_g}$$

$$E_g = 2\,000\,000 \text{ kVt/saat}$$

$$\dot{I}_g = 145 \text{ ton}$$

$$E = \frac{2\,000\,000 \text{ kVt/saat}}{145 \text{ ton}} = 13\,800 \text{ kVt/saat}$$

Here, E is the energy required for the production of 1 ton of aluminum, E_d is the daily electrical energy consumed in the electrolysis process, and P_g is the amount of primary aluminum produced per day. In addition to conventional energy sources, Azerbaijan's green energy resources are sufficient to support the current aluminium industry and even higher levels of production. For example, the electricity generation capacity from hydropower plants alone exceeds 1,100 MW, while

AzərAlüminium’s current energy consumption is less than 100 MW. Moreover, planned future projects in alternative energy sources will add over 500 MW, providing strong prospects for the development of the country’s green industry.

The preparation of a Green Production Passport (GPP) for modern aluminium production represents a significant strategic innovation and constitutes a fundamental requirement for sustainable operation in the global business environment (Table 5).

Table 5.

Indicators of GAC on the Green production passport (GPP)

What was consumed during the initial production of 1 ton of aluminum in the Ganja aluminum complex.	
Anode	0.408 T
CO ₂ emissions (indirect)	0 T
CO ₂ emissions (direct)	1.49 T
Energy consumption	13.800 kW-h

Source: Compiled by the author

In the green procurement (GP) management system, the primary focus is on the supply of raw materials. In contrast, green transportation (GT) management deals with the delivery of finished products to their required destinations, addressing logistical challenges and operational issues. The transportation system, which has multiple characteristics, is influenced primarily by two factors:

- Geography and infrastructure
- Business strategies

During periods of rapidly rising global inflation, sudden increases in transportation costs have contributed to higher prices for goods and created obstacles in supply-and-demand processes. In 2021, international transportation costs were observed to have increased fourfold compared to previous years (Figure 3).

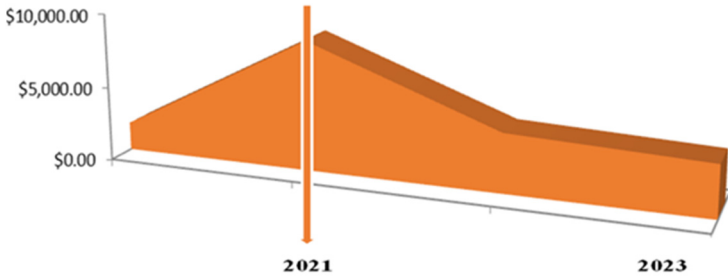


Figure 3. An illustration of the dramatic increase in shipping costs at GAC due to the container

Source: Prepared by the author

Prioritizing green transportation (GT) in the aluminium industry provides both environmental benefits and economic advantages. For the same distance, the costs of trucking are higher than those of rail or maritime transport. Figure 4 visually presents the relevant data for shipments from Azerbaijan to the United States.



Figure 4. GT trajectory from GAC to the USA and transportation costs per 1 ton of cargo (2023)

Source: Prepared by the author

By utilizing simulation modeling—a valuable mathematical and analytical tool for studying complex systems—it is possible to enhance the efficiency of GSCM initiatives in the aluminium sector.

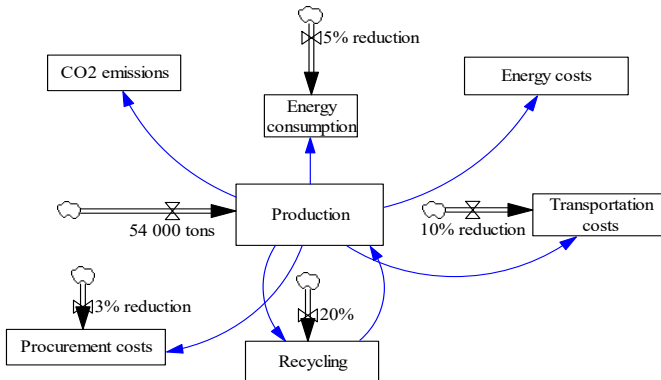


Figure 5. Descriptive structure of the GAC simulation model

Source: Compiled by the author using Vensim software

For the simulation model, which has been prepared in a visual format, a system of various tasks was established (Figure 5). The existing tasks are presented in Table 6. Mathematical calculations were performed for all tasks, and the results are shown in Table 7. The final outcome of testing the simulation model indicates that a hybrid strategy—combining energy savings, transportation optimization, and efficient raw material procurement—can achieve an annual total profit of USD 4,558,500.

Table 6.
Presenting 5 different tasks to be evaluated in the simulation model

Task 1	Main context	The current system is evaluated without any changes
Task 2	Organization of energy efficiency	5% reduction in energy consumption
Task 3	Transport optimization	10% reduction in shipping costs
Task 4	Optimization of raw material purchases	3% reduction in procurement costs
Task 5	A hybrid approach	Combining a 5% reduction in energy consumption with a 10% reduction in transport costs

Source: Prepared by the author

The effectiveness of the integrated hybrid strategy in significantly improving overall financial performance can be observed through the application of the simulation model. In the second paragraph, entitled “Structural Design and Core Strategies of Green Supply Chain Management at the Ganja Aluminium Complex,” a GSCM department was proposed for the organizational structure of AzərAluminium at GAC. A new model was applied for the efficient management of green production within the aluminium industry, and green business strategies were introduced to support sustainable development.

Table 7.
Results of the tested simulation model

	General system dynamics (Task 1)	Energy efficiency (Task 2)	(Transport optimization (Task3)	Procurement efficiency (Task 4)	Hibrid approach (Task 5)
Total energy consumption	745.200 mV	708.540 mV	745.200 mV	745.200 mV	708.540 mV
Total energy costs	18.600.000\$	17.713.500\$	18.600.000\$	18.600.000\$	17.713.500\$
Transportation costs	10.800.000\$	10.800.000\$	9.720.000\$	10.800.000\$	9.720.000\$
Raw material costs	86.400.000\$	86.400.000\$	86.400.000\$	83.808.000\$	83.808.000\$
Total costs	115.800.000\$	114.913.500\$	114.720.000\$	113.208.000\$	111.241.500\$
CO₂ emissions	80.460 (t-year)	80.460 (t-year)	80.460 (t/year)	80.460 (t/year)	80.460 (t/year)
Recynling	10.800 (t-year)	10.800 (t-year)	10.800 (t-year)	10.800 (t-year)	10.800 (t-year)

Source: Performed by the author

The structural operation of GSCM has a complex character within the organizational framework and is interconnected with all departments in some form. The main departments directly included in the operational plan are as follows:

- Ganja Production Complex (GPC)
- Commercial Department (CD)
- Business Development Department (BDD)

Within GAC, the GSCM system is most closely linked to the GPC and CD. Its organization can function autonomously within the corporate structure while operating in a hybrid mode, synthesizing activities across all related departments.

To implement eco-design from a global perspective down to the regional level, and from general principles to specific applications, a range of methods and tools is available. One of the most effective instruments for green economy and business design is the “LiDS Wheel” model. This model initially analyzes the environmental impacts of two different products, with its primary feature being the ability to assess a new product while maintaining the old design for comparison. Figure 6 illustrates the first application of this model in the context of a sustainable aluminium industry.

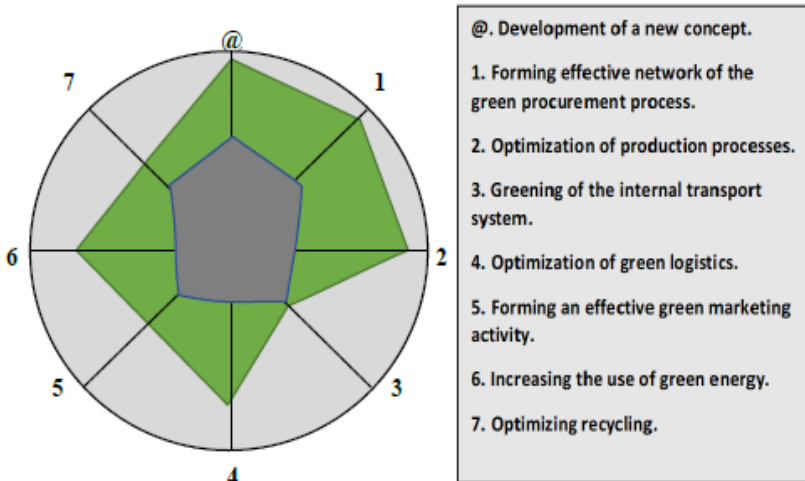


Figure 6. Application of the LiDS eco-design model to the aluminum industry

Source: Designed by the author

In the final paragraph, entitled “**The Essence of Inert Anode Technology and Its Eco-Economic Analysis at the Ganja Aluminium Complex,**” the key features of the revolutionary inert anode technology—implemented as a pilot by leading global aluminium companies and technological facilities—are discussed. An eco-economic analysis of this technology was conducted at GAC, and a new strategic pathway for the sustainable development of Azerbaijan’s aluminium industry was proposed.

Inert anode technology represents a completely innovative approach to aluminium production, as the use of alternative anodes during electrolysis effectively eliminates greenhouse gas emissions. This breakthrough aims to transform the aluminium industry into an environmentally clean system that also saves capital and energy. Major global companies such as Alcoa, Rio Tinto, Rusal, and Hydro are at the forefront of developing and advancing this technology. In 2021, Rusal successfully conducted initial trials of inert anode technology, operating at 140,000 amperes and achieving industrial-scale aluminium production capable of producing approximately 1 ton per cell per day.

The eco-economic assessment of this revolutionary inert technology and its recommendation as a necessary project for future implementation is of critical importance. At GAC, if the 0.8 tons of CO₂ emissions generated from perfluorocarbon processes due to the use of conventional carbon materials are included, the total CO₂ emissions amount to 2.3 tons per ton of primary aluminium.

Thus, by applying inert anode technology in Azerbaijan, it is possible to transform the aluminium production process into a fully green industry with zero direct carbon emissions, effectively saving 2.3 tons of CO₂ per ton of aluminium produced.

$$\begin{aligned} \dot{I}AT &= 0T \\ KAT &= 2.3T \\ CO_2 &= \dot{I}AT - KAT = -2.3T \end{aligned}$$

Here:

- IAT = Inert Anode Technology
- CAT = Carbon Anode Technology

From an eco-economic evaluation perspective, a specialized method can also be applied. At the global level, it is useful to analyze the monetary costs associated with each ton of CO₂ emissions using the Social Cost of Carbon (SCC). The SCC is an important statistical and methodological tool that accounts for multiple factors, including the negative health impacts caused by climate change, property damage, and reductions in productivity, incorporating economic, social, and environmental effects.

Scientific calculations in the United States officially estimate that the environmental damage per ton of CO₂ emissions is USD 51. By rounding the annual production capacity to a minimum of 50,000 tons, the total Environmental Cost (EC) of the aluminium industry for a complex like GAC can be determined using existing statistical data:

$$EM = CO_2 \times K_{SX} \times I = - 2.3T \times 51\$ \times 50\ 000T = -5\ 865\ 000\$$$

According to the results, for an aluminium complex with a minimal production capacity of 50,000 tons, the implementation of inert anode technology would provide an annual total ecological benefit of approximately USD 6 million. The overall results are presented in Table 8.

CONCLUSION AND RECOMMENDATIONS

The research conducted within the framework of this dissertation has identified the potential for implementing Green Supply Chain Management (GSCM) in the aluminum industry and assessed sustainable development perspectives as follows:

1. A conceptual framework for GSCM was developed, and the transformational process from a traditional supply chain to a green alternative was analyzed.
2. The relationship between carbon emissions and economic activity was examined through GSCM, identifying key directions necessary for sustainable economic development.
3. Using the ARIMA model, CO₂ emissions in the aluminum

- industry were forecasted up to 2030, indicating a projected 6% reduction compared to 2022 levels.
4. The technological infrastructure and strategic development directions of Azerbaijan's aluminum industry were analyzed, revealing that the industry currently accounts for a 7% share of the non-oil export sector.
 5. Azerbaijan's renewable energy potential exceeds 1,300 MW, while the energy consumption of aluminum production accounts for only 6–7% of this capacity, ensuring full energy provision and additional capacity for future expansion.
 6. For the first time, a Green Production Passport (GPP) was prepared for the Ganja Aluminum Complex (GAC), emphasizing the strategic importance of producing products that comply with ecological standards for US and European markets.
 7. Results from the simulation model using Vensim indicate that optimizing the supply chain can yield an additional annual profit of USD 4,558,500.
 8. A multifunctional organizational model and the LiDS wheel demonstrated the advantages of integrating green management into the aluminum industry.
 9. The dissertation assessed the potential of green economic transition in Azerbaijan's aluminum sector, proposing innovative approaches for sustainable industrial development.
 10. The implementation of Inert Anode Technology (IAT) in aluminum production minimizes CO₂ emissions, providing an estimated annual environmental benefit equivalent to USD 5,865,000.

RECOMMENDATIONS

1. The GSCM system in the aluminum industry should be organized on a unified platform, integrating green procurement, production, and transportation stages.
2. Low-carbon and energy-efficient technologies should be widely promoted and adopted in aluminum production to enhance environmental compliance.

3. Eco-efficient strategies should be applied in raw material procurement, production, and logistics, with continuous monitoring and sustainability criteria established based on the green supply chain model.
4. Azerbaijan should maximize its renewable energy potential to fully support aluminum production and accommodate additional energy demand.
5. A Green Supply Chain Management platform should be established at the Ganja Aluminum Complex, enabling coordinated operations with other organizational units.
6. Transition to Inert Anode Technology should be implemented to achieve long-term sustainable development and enable aluminum production with near-zero carbon emissions.

**THE AUTHOR HAS PUBLISHED THE FOLLOWING
SCIENTIFIC WORKS ON THE TOPIC OF THE
DISSERTATION:**

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A handwritten signature in blue ink, consisting of stylized initials and a surname, followed by a horizontal line.

The defense of the dissertation will be held on 15 may 2026 at 11⁰⁰ at the meeting of the Dissertation Council FD 1.10 operating under the Institute of Economics of the Ministry of Science and Education of the Republic of Azerbaijan.

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