ECOLOGY

The object of the study is the process of decarbonization of civil aviation by switching to environmentally friendly fuels, which is relevant for the majority of countries in the world seeking to reduce the carbon footprint of air transport. The study uses methods that comply with international standards, which allowed to draw conclusions applicable in a global context. Due to their features and characteristics, the results of the study made it possible to form a clear idea of the global industry program to reduce and offset carbon emissions, as well as to establish the level of readiness of the civil aviation of the Republic of Kazakhstan and related industries to switch to alternative types of aviation fuel. The constructed mathematical models of the dependence of the efficiency indicator Y (carbon footprint level) on a set of factor features Xi and made it possible to prove the presence of multicollinearity in the array of mutually independent factors affecting the efficiency indicator Y, as well as to prioritize them based on the strength of their influence on the size of the carbon footprint of air transportation. It is emphasized that the process of switching aviation to bio- and synthetic aviation fuel is complicated by the lack of a Strategy and related documents on the implementation of activities related to the transition of aviation to new generation fuels. The key points of constructing the algorithm for the transition of civil aviation to environmentally friendly fuel have been identified, which ensured the construction of its simulation model. The practical application of the proposed algorithm for the transition of civil aviation to new-generation fuel should become the fundamental basis for the formation of the country's Roadmap for the transition of aviation to SAF and LCAF

Keywords: algorithm for the transition of aviation to environmentally friendly fuel, decarburization of aviation, carbon footprint of aviation

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DEVELOPMENT OF AN ALGORITHM FOR THE TRANSITION OF CIVIL AVIATION TO ECOLOGICALLY CLEAN AVIATION FUEL

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1. Introduction

The growing aviation market makes a significant contribution to the economic development of each state but also inevitably leads to environmental problems (an increase in carbon emissions), leading to global climate change. Although the sector accounts for less than 2 % of global CO_2 emissions, the awareness of the magnitude of this threat requires appropriate measures to be taken. Therefore, having studied the carbon footprint of the air transport industry and the possibilities for its reduction, ICAO introduced the CORSIA scheme (Carbon Offsetting and Reduction Scheme for International Aviation), aimed at ensuring carbon-neutral growth from international aviation [1]. Primarily, this is achieved through the transition to next-generation fuel, which, as early as 2009, was recognized as an important means of reducing the carbon footprint of international aviation at the first ICAO Conference on Aviation and Alternative Fuels (CAAF) (Rio de Janeiro, Brazil) [2]. The development and transition to sustainably produced types of alternative aviation fuel (SAF) have been included as a key component in ICAO's "basket of measures" [2] to achieve a zero-carbon balance in international aviation.

In October 2017, following the second ICAO International Conference on Sustainably Produced Alternative Fuels (Montreal and Mexico City), a mechanism was approved to ensure a smooth transition from the use of global market-based measures (MBM) to the use of sustainably produced aviation fuels (SAF) during the period from 2021 to 2035 [2].

The outcome of the Third ICAO Conference on Aviation and Alternative Fuels (CAAF/3) (Dubai, United Arab Emirates, November 20–24, 2023) was the agreement by more than 100 countries to create a global framework necessary for the development, implementation, and production of SAF, as well as low-carbon aviation fuel (LCAF), as key elements of LTAG – the collective long-term aspirational goal of achieving net-zero carbon emissions in international aviation by 2050 (41st ICAO Assembly) [3].

Currently, airlines such as ASD, CANSO Europe, ERA, WIZZ, and others have already confirmed their readiness to use SAF. However, voluntary efforts alone are not enough. It is necessary to organize the production of SAF in sufficient volumes, the increase of which will make it more cost-effective for airlines and consumers [3]. Under the current conditions (production volumes and prices of SAF), as experts from Batik Air (Indonesia), Azul Conecta (Brazil), Luzair (Portugal), and other airlines assert, it is more profitable for aircraft operators to offset their CO_2 emissions by purchasing carbon credits than to cover the price gap between fossil fuels and SAF [4].

However, in April 2024, the European Parliament approved a reform of the greenhouse gas emissions trading system. It provides for the abolition of free quotas for the aviation sector by 2026 and the payment of compensation obligations by airlines or the purchase of free carbon emission units. Their cost on the carbon market (in particular, according to Eurostat) has increased rapidly in recent years and reached a maximum level of 112.3 euros/t of carbon emissions in 2023.

All of the above suggests that civil aviation urgently needs to make the transition to a new generation of fuel. However, today only a few countries have taken measures to implement this transition. The primary reason for this situation is the lack of both a Transition Strategy and clear guidelines for its implementation, which significantly complicates attracting investment and, accordingly, the process of reducing the carbon footprint of aviation. Therefore, research into the development of an algorithm for the transition of civil aviation to new generation fuel, as a fundamental basis for constructing a Strategy and Roadmap for the transition of civil aviation to environmentally friendly fuel by 2050, is quite relevant.

2. Literature review and problem statement

An analysis of literary sources gives grounds to assert that the issues of civil aviation decarburization are quite actively discussed in scientific publications, since the rapid pace of air transportation development significantly exceeds the rate of reduction of the carbon footprint of aviation, and the ways of decarburization of the industry are quite limited. In particular, in the article [5] the researcher focuses on possible options for reducing carbon emissions by aviation. However, their plausibility and feasibility in the short, medium and long term are not sufficiently substantiated due to the lack of an assessment of the existing potential, justification of the closeness of the relationship between factors and the result (the carbon footprint of aviation), as well as ignoring the scenario approach when making forecasts for the future.

A group of researchers in [6] emphasizes the difficulty of reducing carbon emissions in the aviation sector. Airframe and engine designs have been improved over decades to achieve higher levels of fuel efficiency. However, it has not been possible to achieve carbon neutrality in aviation. The authors conducted a broad review of the scientific literature on the issue of decarburization of air travel, identified the factors influencing the carbon footprint of aviation. However, the results of their research are not of an applied nature, which is not enough to find ways and take decisive measures to transition aviation to a new generation of fuel.

Chinese scientists, guided by statistical data on Chinese civil aviation, developed a model aimed at identifying the factors influencing changes in the level of CO_2 emissions in the aviation sector [7] (2023), which allowed them to build a number of scenarios for reducing carbon emissions for the period up to 2040. However, the issue of constructing an algorithm for the transition of civil aviation to low-carbon fuel was completely missed by the researchers, which, in our opinion, is unacceptable, since not only aviation, but also its related industries play an important role in the implementation of this transition.

The study [8] conducted a more complete analysis of the transition of aviation to SAF: the need for SAF, the costs of switching to low-carbon aviation fuel, the reduction of CO_2 emissions, and other expected effects were studied. Researchers have developed many scenarios for the development of aviation for the period up to 2100 [8], thus proving that there are no other realistic solutions for reducing aviation carbon emissions without a transition to bio-jet and synthetic fuels in the medium term, as well as without a transition to electric and hydrogen-powered aircraft in the long term. However, the issues of investing in the transition have become secondary, which raises doubts about the realism of the forecasts made by researchers.

The article [9] provides a more detailed analysis of the transition of civil aviation to SAF, where investment issues are of primary importance. The researchers emphasize that with significant investments in technology development and aircraft manufacturing, it is imperative to invest capital in related industries. Otherwise, aviation will either fail to achieve the set goal of decarburization, or will capture an excessive amount of resources that are critically needed, in particular, to ensure food and energy security of countries [9]. The authors focus on the existing potential for SAF production, but there are no forecasts for either the near or the long term, which significantly complicates the understanding of the expected prospects.

In the article [10], the researchers raise the issue of existing international and national policies for the transition of aviation to SAF, which provide a number of incentives for achieving the set goal and a complete absence of any restrictions. Using the example of Dutch aviation, the authors prove that the transition to SAF will lead to an increase in the cost of cargo and passenger transportation, and, accordingly, to a decrease in the number of passengers by 15 % by 2050. Scientists prove that only with the support of the state and international organizations, as well as a revision of the aviation quota system, it is possible to maintain the growth rate of the industry and ensure a reduction in the level of carbon emissions [10]. But, unfortunately, the issues of developing a Strategy, Roadmap and Plan for the implementation of the transition of aviation to SAF, as the main components of state regulation, remained without attention.

Researchers in [11] presented a comprehensive study of feature selection for the analysis of aviation environmental impacts. The methodology they developed consists of five steps: data integration and feature engineering, unsupervised information-based feature filtering, large-scale computer modeling, supervised single-objective feature selection, and supervised multi-objective feature selection. However, its practical application remains controversial, as it has quite a few pros and cons.

Thus, it is possible to conclude that despite quite active research into ways to reduce the carbon footprint of aviation, there are still many unresolved organizational issues and issues of state regulation of the transition of aviation to SAF.

All this indicates the advisability of conducting research to develop a clear algorithm for the transition of civil aviation to new-generation fuel.

3. The aim and objectives of the study

The aim of the study is to develop an algorithm for the transition of civil aviation to new-generation fuel, as a fundamental basis for constructing a Roadmap for the transition of civil aviation to SAF and LCAF.

To achieve this goal, the following tasks have been formulated:

– to study the sectorial program for reducing and compensating carbon emissions;

– to analyze the readiness of Republic of Kazakhstan's civil aviation to switch to new-generation fuel;

– to identify key factors influencing the carbon footprint of Republic of Kazakhstan's civil aviation using the example of the country's leading airline;

– to develop a simulation model for constructing an algorithm for the transition of civil aviation to new generation fuel.

4. Materials and methods

The object of the study is the process of decarbonization of civil aviation by switching to environmentally friendly fuels, which is relevant for the majority of countries in the world seeking to reduce the carbon footprint of air transport.

The possibility of accelerating the process of decarbonization of civil aviation by developing a clear algorithm for its transition to new generation fuel.

A simulation model of the algorithm for the transition of Kazakhstan's civil aviation to new-generation fuels has been proposed, which can serve as a fundamental basis for creating a Roadmap for the transition of Kazakhstan's civil aviation to SAF and LCAF, since it provides answers to such important questions as: who, what and when. In the aviation sector, such a model is proposed for the first time.

The simplifications adopted in the work are related to the fact that at present the system of collecting information and exchanging it in the sphere of civil aviation in the Republic of Kazakhstan is not transparent enough, which complicates the conduct of research. Therefore, as a simplification, a reduced set of indicators was selected for modeling based on available sources of reliable information.

The materials for this study were: the results of the WORLD EMISSIONS CLOCK monitoring, published by the non-profit organization World Data Lab, 2023; AR6: Climate Change 2023 Summary Report from the Intergovernmental Panel on Climate Change (IPCC); statistical data from the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan; regulatory legal acts; corporate reports of Air Astana; reports of researchers from the Civil Aviation Academy (Almaty).

The study was conducted using mixed methods: sample statistical, experimental, econometric modeling, scenario forecasting, visualization and others. The creation of mathematical models for forecasting was carried out using the methods of correlation and regression analysis.

Although this study focuses on the experience of the Republic of Kazakhstan, the problem of transition to environmentally friendly fuels is relevant for many countries seeking to reduce the carbon footprint in aviation. The study uses methodologies that comply with international standards, which allows to draw conclusions applicable in a global context. Analysis of the transition to new fuel in the Republic of Kazakhstan can serve as a model for other regions facing similar challenges. This approach demonstrates that the study goes beyond the region and has international significance.

The World Data Pro platform was used in the study, Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan.

5. Results of developing the algorithm for transitioning civil aviation to next generation fuel

5. 1. Sectorial program for reducing and compensating carbon emissions

According to the results of the WORLD EMISSIONS CLOCK monitoring, published by the non-profit organization World Data Lab, 2023 was the year with the highest recorded emissions ever. Undoubtedly, each of the countries that signed the Paris Agreement [11] is taking measures to reduce carbon emissions, but not all are able to achieve rapid success, as they have completely different starting points and trajectories.

World Data Lab, after analyzing per capita carbon dioxide emissions, created a world map (Fig. 1) that categorizes countries into three groups: high, medium, and low levels of CO_2 emissions.

Currently, a reduction in greenhouse gas emissions is observed across much of the Northern Hemisphere, as well as in Australia and New Zealand. For the first time, China and the United States-global leaders in carbon emissions are included in this group. Newcomers to this group also include Australia, Portugal, Peru, and the Republic of Kazakhstan.

Republic of Kazakhstan plans to continue aligning with decarbonization trends, setting a goal to reduce carbon emissions to 324.9 million tons of CO_2 equivalent by 2030, and to achieve carbon neutrality by 2060 [12].

However, as noted in [13], analysis of the current situation shows that in order to achieve these goals, it is necessary to radically improve the existing carbon regulation policy in the Republic of Kazakhstan [13], especially in dynamically developing sectors, including civil aviation.

Therefore, one of the promising goals for the development of civil aviation in Republic of Kazakhstan is to reduce climate impact and achieve a net-zero balance of carbon emissions by 2050. This goal continues the Paris Agreement [14], the AR6 Synthesis Report: Climate Change 2023 by the Intergovernmental Panel on Climate Change (IPCC) [15], and the three global goals previously adopted by ICAO to reduce aviation's climate impact, specifically:

– short-term: To increase aviation efficiency by 1.5 % per year;

– medium-term: To reduce net CO_2 emissions through carbon-neutral growth;

– long-term: To achieve a net-zero balance of carbon emissions by 2050 [15].

Thanks to the implementation of new aircraft technologies, increased operational efficiency, and improved industry infrastructure, aviation has exceeded the short-term goal, achieving an average improvement of 2.1 %, which translates to a 22.8 % increase in efficiency. Fuel consumption and CO_2 emissions per passenger-kilometer have decreased by 54 % compared to 1990. The industry continues to strive for further efficiency improvements and CO_2 emission reductions, as evidenced by the three comprehensive scenarios developed for ICAO's Long-Term Plan (LTAG) to achieve net-zero carbon emissions in international aviation by 2050 [16]. These scenarios address issues of "readiness, feasibility, and ambition" within the sector (Fig. 2) [17].

Scenario 1 (IS1) represents a "high level of readiness/feasibility and low level of ambition." It is the least favorable scenario, reflecting current (2021) expectations regarding the emergence of future technologies, operational efficiency, and availability of fuels [17]. IS1 requires minimal implementation efforts.

Scenario 2 (IS2) describes a "medium level of readiness/feasibility and medium level of ambition." IS2 is a more ambitious scenario, involving rapid deployment of future technologies, improved operational efficiency, and higher fuel availability. Among the three scenarios, IS2 requires moderate implementation efforts [17].

Scenario 3 (IS3) represents a "low level of readiness/feasibility and high level of ambition." IS3 is an extremely ambitious scenario, involving the maximum possible efforts in terms of deploying future technologies, operational efficiency, and fuel availability [17]. IS3 requires the greatest implementation efforts among the three scenarios and a high level of internationally coordinated systemic changes. This includes significant and widespread alterations to airport and energy infrastructure [18].

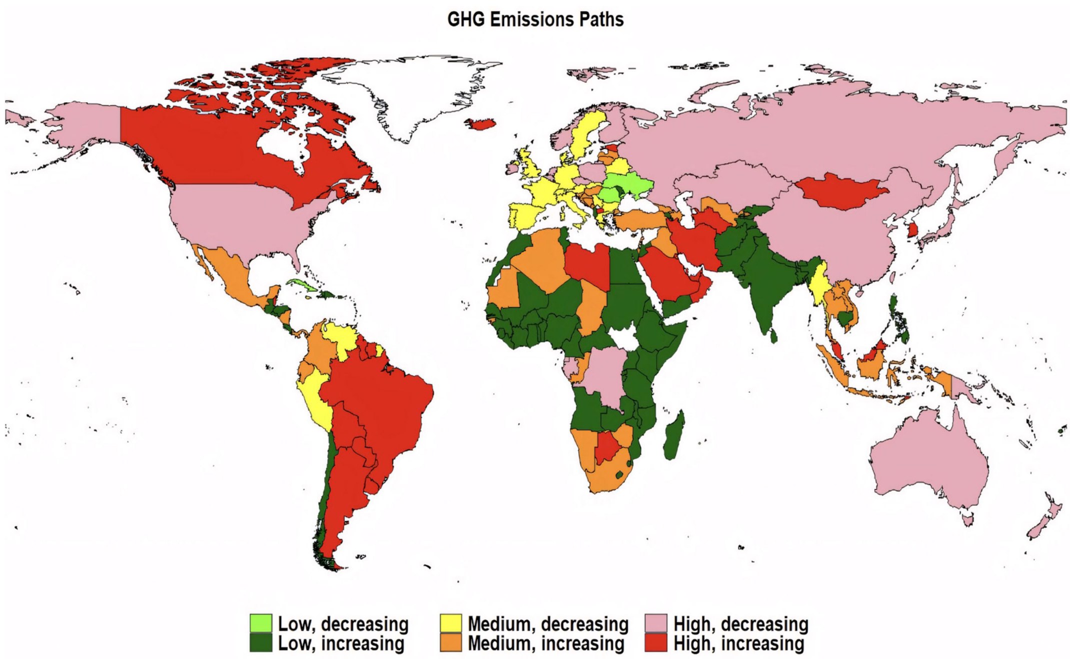
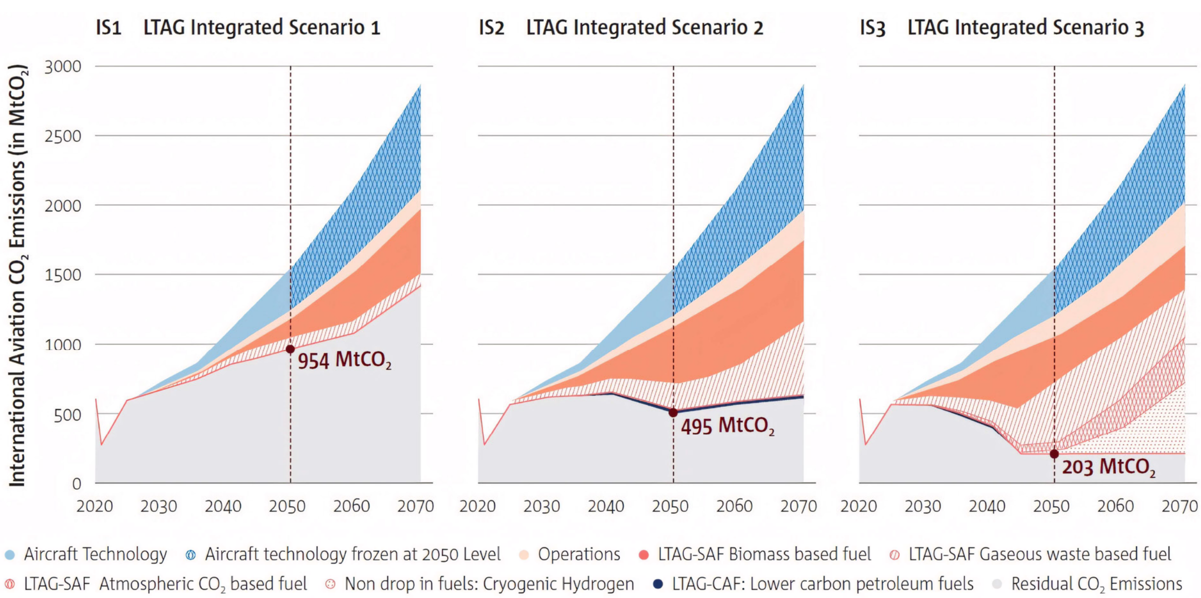


Fig. 1. World map of greenhouse gas emissions per capita in 2023 [11]



a *b* *c*

Fig. 2. Scenarios for reducing the carbon footprint of international aviation According to ICAO forecasts [18]: *a* — IS1 LTAG integrated scenario 1; *b* — IS1 LTAG integrated scenario 2; *c* — IS1 LTAG integrated scenario 3

Based on IS1-IS3, CO_2 emissions from civil aviation could be nearly halved by 2050 by environmentally friendly aviation fuels. Therefore, according to the ICAO Consolidated Statement on Environmental Policy and Practice [19], each country that has voluntarily committed to participate in CORSIA (specifically 115 countries as of the end of 2023) is obligated to gradually transition to the use of SAF for international flights [20].

Republic of Kazakhstan is no exception. As the first among the CIS countries to join the International Civil Aviation Organization (ICAO) program for the development of SAF, Republic of Kazakhstan has decided to gradually transition its aviation sector to "clean" Jet A-1 fuel [21]. To develop a roadmap for the transition of Republic of Kazakhstan's civil aviation to next-generation fuel, the "1st Republic of Kazakhstan Aviation Dialogue: Energy Transition for Sustainable Development and Implementation of Central Asia's Transit Potential" was held in Astana in May 2023 [22]. The event addressed issues such as reducing emissions in the aviation sector (Fly Net Zero 2050), opportunities for sustainable aviation fuel production in Republic of Kazakhstan, the country's transition to Jet A-1 aviation fuel, the impact of geopolitical tensions and economic sanctions on the development of Central Asia's transit potential, and other related topics [22].

However, developing the roadmap requires a thorough examination of the readiness and ability to transition to "clean" aviation fuel, not only within the civil aviation sector but also in related industries (such as agriculture, transportation, etc.), which is the focus of this research.

5. 2. Assessment of Republic of Kazakhstan's civil aviation readiness for transition to new-generation fuel

Currently, Kazakh airlines operate international flights to 27 countries across 103 routes. According to the ICAO document: CORSIA Central Registry (CCR): Information and Data for Transparency [23] (referencing the Civil Aviation Committee of the Ministry of Industry and Infrastructure Development of Republic of Kazakhstan), CO_2 emissions from Kazakh airlines in 2022 amounted to over 800,000 tons. Specifically, data for each international route is detailed in Fig. 3.

By the end of the year, the opening of 9 new international routes to Doha, Kuala Lumpur, Ankara, Karachi, Lahore, Jeddah, Muscat, Prague, and Tel Aviv is expected. Additionally, flights to Mumbai, Hong Kong, Vienna, Tokyo, Singapore, New York, and other cities are planned by 2025 [24]. Consequently, a rise in carbon emissions is projected, which is unacceptable in the context of the escalating climate crisis.

However, the carbon footprint of civil aviation is determined not so much by the number of international routes as by the condition of the aircraft in Republic of Kazakhstan's aviation fleet. According to AirFleets.net [25], as of January 1, 2024, there were 99 aircraft in Republic of Kazakhstan civil aviation with an average age of 11.2 years (Table 1).

The oldest aircraft in Republic of Kazakhstan are Boeing 757, Boeing 737, and Fokker 70/100 models (Table 2), which are used by Republic of Kazakhstan Gvmt, SCAT Airlines, and Sunday Airlines. Their operational age exceeds 30 years.

Thus, the visualization of the state of the aircraft fleet of Republic of Kazakhstan's airlines as of January 1, 2024, can be presented as follows (Fig. 4, *a*, *b*).

In the first place, both in terms of the number of aircraft and their "newness," is the country's largest carrier, Air Astana Group. The average age of the company's airliners in 2022 was 3.9 years. The Air Astana fleet mostly consists of Airbus A320 and Airbus A321 models, which are fuel-efficient and environmentally friendly.

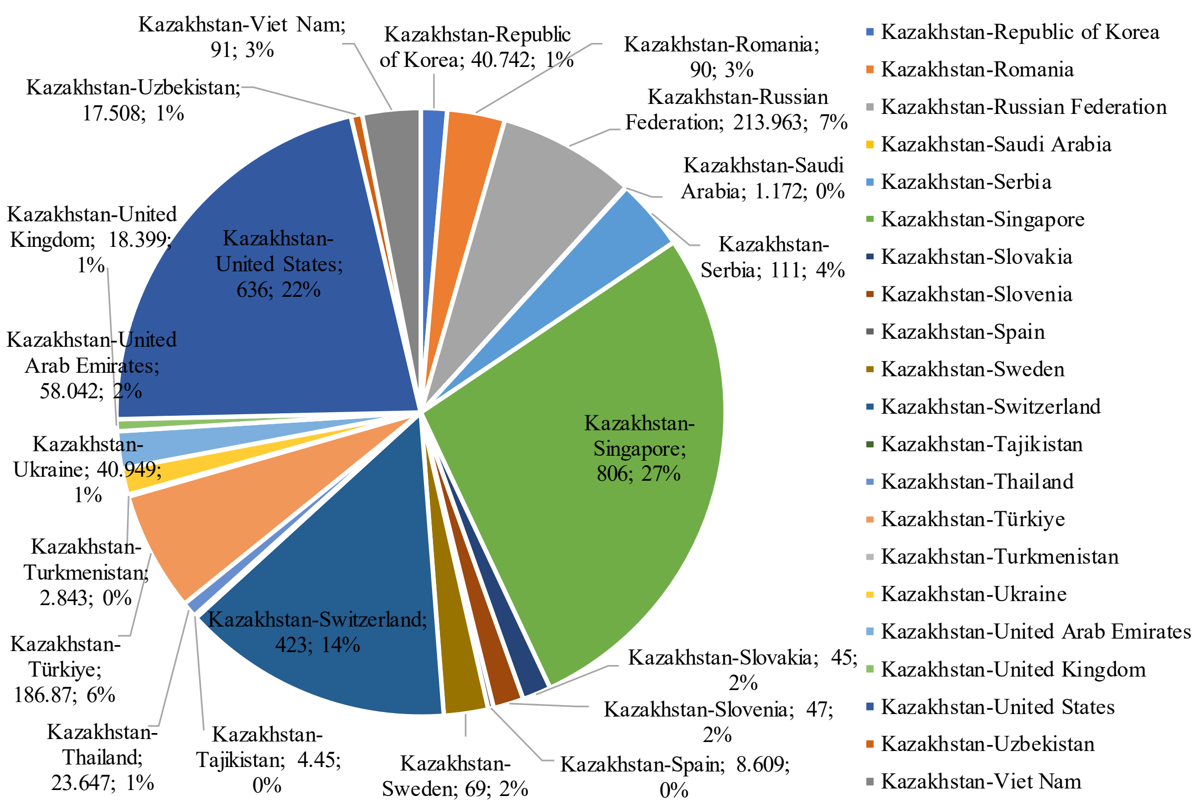
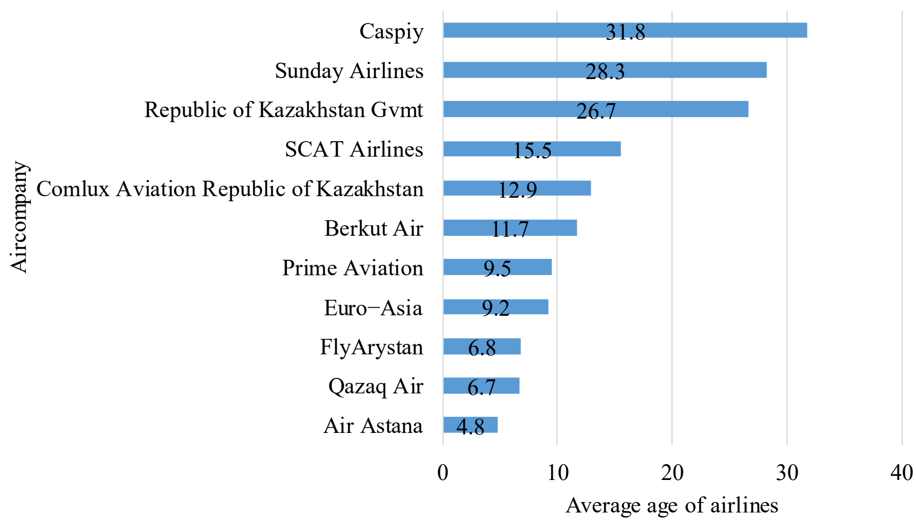
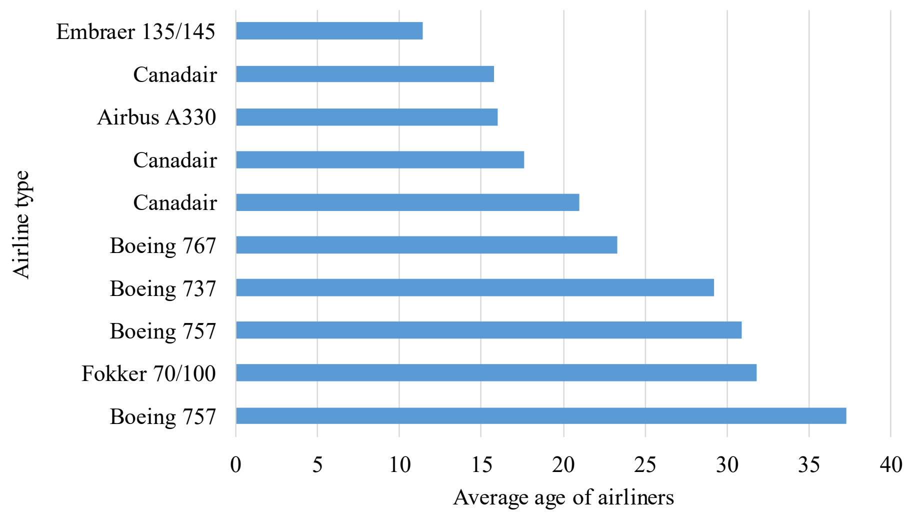


Fig. 3. CO_2 emissions by Kazakh civil aviation according to the ICAO document: CORSIA Central Registry (CCR): information and data for transparency, in thousand tons [23]



a



b

Fig. 4. Average age of aircraft of Kazakh airlines as of 01.01.2024 [25]: *a* — average age of aircraft by model; *b* — average age of aircraft by airline

Table 1

Aircraft of Republic of Kazakhstan's airlines fleet as of January 1, 2024 [25]

Airline	Number of aircrafts	Average age of aircrafts
Air Astana	29	4.8
Qazaq Air	5	6.7
FlyArystan	18	6.8
Euro-Asia	3	9.2
Prime Aviation	1	9.5
Berkut Air	3	11.7
Comlux Aviation Republic of Kazakhstan	3	12.9
SCAT Airlines	31	15.5
Republic of Kazakhstan Gvmt	2	26.7
Sunday Airlines	3	28.3
Caspiy	1	31.8
Total for the Republic of Kazakhstan	99	11.2

Table 2

The Top 10 oldest aircraft in the air fleet of Republic of Kazakhstan's airlines as of January 1, 2024 [25]

No.	Aircraft model	Average age of aircraft	Number of aircraft	Airline
1	Boeing 757	37.3	1	Republic of Kazakhstan Gvmt
2	Fokker 70/100	31.8	4	Caspiy
3	Boeing 757	30.9	2	Sunday Airlines
4	Boeing 737	29.2	6	SCAT Airlines
5	Boeing 767	23.3	1	Sunday Airlines
6	Canadair	21.0	5	SCAT Airlines
7	Canadair	17.6	1	Comlux Aviation Republic of Kazakhstan
8	Airbus A330	16.0	1	Republic of Kazakhstan Gvmt
9	Canadair	15.8	1	Berkut Air
10	Embraer 135/145	11.4	3	Comlux Aviation Republic of Kazakhstan

5. 3. Identification of key factors influencing the carbon footprint of civil aviation in Republic of Kazakhstan

The Air Astana Group includes the full-service carrier Air Astana and the budget airline FlyArystan [26]. This model allows for the most efficient utilization of economic growth opportunities while targeting various markets and geographic regions.

According to data from the Air Astana Group, the composition of the company's aircraft fleet from 2013 to 2022 is characterized by the information in Table 3.

Of the total number of aircraft in the Air Astana Group's fleet, 35 are fuel-efficient and environmentally friendly. In 2023, the Group received the latest aircraft: Airbus A321LR in October and the Airbus A320neo in November. As of December 31, 2023, the fleet size of the Group had increased to 49 aircraft (under a single operator certificate (AOC), with 31 aircraft operated by Air Astana and 18 by FlyArystan), including 41 narrow-body Airbus A320 family aircraft, 5 narrow-body Embraer E190-E2 aircraft, and 3 wide-body Boeing 767 aircraft. The new, more modern, and environmentally friendly aircraft have reduced the environmental impact of air travel. In particular, the Airbus A320neo family has achieved a fuel consumption reduction of up to 20 % and a corresponding reduction in CO_2 (NOX) emissions by 1/5 compared to the previous generation of A320ceo aircraft [29].

Thus, thanks to its young and modern fleet of 43 aircraft (2022), the Air Astana Group has provided regular, direct, and transit flights on 88 routes to 22 countries (including Republic of Kazakhstan). The two differentiated but complementary brands of the Group-Air Astana (its full-service brand and leading Kazakh airline) and FlyArystan (its budget airline brand)-have allowed the company to target various customer markets and geographic regions [29], thereby ensuring growth in business performance even in challenging years for the industry (post-pandemic years, years of airspace closures over Ukraine, etc.) (Table 4).

At the same time, according to the Group Air Astana Development Strategy, by 2026 the company plans to double its fleet to ensure more than a twofold increase in passenger traffic through increasing flight frequency, entering new markets, and expanding its route network [30]. However, as previously noted, with the increase in transport volumes, the amount of carbon emissions also rises, as can be seen from the data in Table 5.

From 2013 to 2022, the fuel consumption of Air Astana's aircraft increased twofold, reaching 319.9 thousand tons. However, during this period, the intensity of greenhouse gas emissions decreased by nearly 10 %.

By achieving the objectives outlined in Air Astana's development strategy for the period up to 2026 [30], the company has not only reduced its carbon footprint but also improved its performance metrics (Table 6).

Table 3

Fleet composition of Air Astana Group from 2013 to 2022 [26–29]

No.	Number of aircraft	Year									
		2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1	Boeing 767	4	3	3	3	3	3	3	3	3	3
2	Boeing 757	5	5	5	5	5	5	4	2	0	0
3	Airbus A320/321	12	12	12	13	13	15	18	24	28	35
4	Embraer 190–E2	8	9	9	9	10	10	10	5	5	5
5	Airbus A319	1	1	1	2	2	2	0	0	0	0
6	Total	30	30	30	31	32	34	35	34	36	43
7	Average age	6.4	5.5	6.8	7.5	8.2	8.3	6.5	5.1	4.7	3.9

Table 4

Performance indicators of Air Astana Group for 2013–2022 [26–29]

Indicators	Year									
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Number of aircraft	30	30	30	31	32	34	35	34	36	42
Number of routes	61	62	64	65	66	69	69	74	84	88
Including domestic	18	19	19	20	20	13	21	30	30	15
International	43	40	41	45	46	56	48	44	54	33
Number of countries	16	16	18	20	21	21	21	21	20	22
RPKM, billion	11.4	11.67	12.41	12.72	13.6	14.3	14.7	8.1	13.1	15.9
APKM, billion	7.45	7.55	7.78	7.81	9.0	9.6	10.4	5.8	10.4	13.2
Average aircraft load factor	65.4	64.7	62.7	61.4	66.2	67.1	70.7	71.6	79.4	83.0
Passenger traffic, million passengers	3.68	3.77	3.86	3.75	4.19	4.32	5.12	3.7	6.6	7.4
Including international flights, million	1.56	1.59	1.58	1.66	2.03	2.25	2.31	0.66	2.4	2.6
Domestic flights, million	2.12	2.18	2.28	2.09	2.16	2.07	2.81	3.04	4.2	4.6
Departures, thousand	35.6	37.7	39.4	41.6	43.9	44.7	47.5	30.8	47.1	51.8
Seat-kilometers, thousand	11,483.1	11,724.2	12,433.5	12,740.1	13,943.2	14,267.1	14,781.9	7,904.3	13,063.7	15,921.3
Freight traffic, thousand tons	23.8	19.0	16.6	16.6	19.9	20.0	13.9	13.9	18.8	14.0
Freight ton-kilometers, million	753	748	762	767	771	783	737	731	752	746

Table 5

Dynamics of environmental pollution indicators of Air Astana Group's fleet over 2013–2022 [26–29]

Indicators	Year									
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Fuel consumption, thousand tons	180.6	183.0	188.6	189.3	218.2	232.7	252.1	170.4	261.9	319.9
Greenhouse gas emission intensity (tons CO_2 per RPK)	0.0776	0.0767	0.075	0.075	0.0759	0.0747	0.0653	0.0688	0.064	0.0642
Scope 1 emissions (thousand tons CO_2)	1511.9	1442.3	1409.9	1371.5	1397.2	1065.8	965.3	544.2	836.4	544.2

Table 6

Dynamics of performance indicators for Air Astana Group's business activities from 2013 to 2022 [26–29]

Indicators	Year									
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Total revenue, million USD	967.1	934.8	761.7	621.0	767.5	840.9	898.7	400.3	761.8	1032.4
Net profit, million USD	28	3.5	30.5	−38.5	39.32	5.35	30.03	−93.9	36.2	78.4
EBITDAR, million USD	127.6	112.8	137.3	122.8	150.1	130.9	171.3	33.1	224.9	288.4

Considering all the aforementioned factors influencing the carbon footprint of Air Astana's operations, it is possible to develop a mathematical model to determine the dependence of CO_2 emissions volume (resulting indicator Y) on several key factors (factor indicators Xi). The construction of this model was carried out in the following sequence:

1. By logical generalization and comparison, the patterns of carbon footprint changes were studied, problems in statistical data evaluation were identified, and a statistical database for modeling causal relationships between the resulting indicator Y (CO_2 emissions) and factor indicators Xi, i=1...11 for the period 2013–2022 was formed (Table 7).

2. For visual representation, comparison, assessment, and interpretation of the results of statistical observation (Table 6), a graphical method was used.

Fig. 5 present scatter plots to display the pairs of values "resulting attribute Y - factor attribute Xi" – (Y; Xi), i=1, ..., 11.

On each of Fig. 5, *a–l* the mathematical model of the pairwise linear regression and the coefficients of determination R2 are indicated (constructed using the standard Microsoft Excel package). Visual analysis revealed that factors $X4$ and $X5$ have practically no linear relationship with the outcome Y (R42=0.0773→0; R42=0.0773→0; R52=0.0025→0R52=0.0025→0). Factors $X1$, $X2$, and $X7$ have a strong influence on the outcome Y (R12; R22; R72>0.7R72>0), while other factors have a moderate influence on Y ($X6$, $X10$, and $X11$) and noticeable influence ($X3$, $X8$, and $X9$).

The visualization allowed for the identification of atypical values that distort the general patterns between Y and Xi (i=1, ..., 11) – specifically, the data points (Y; Xi) from 2020 (COVID-19) on most graphs. After filtering the data, the data from 2020 was not used in subsequent calculations.

3. The experimental method and correlation analysis method were used to establish the dependency of the result variable Y (CO_2 emissions) on the set of factor variables Xi.

The selection of factors Xi, i=1, ..., 11, for inclusion in the model $Y=f(Xi)$, i=1, ..., 11 was carried out using the calculated pairwise correlation coefficients r(Y; Xi) between the dependent variable Y and the independent variable Xi, and $r(Xi; Xk)$ between the factor variables Xi and Xk. These coefficients provide a statistical assessment of the strength of the relationship between the corresponding pairs of variables.

The results of the calculations allowed to identify factors $X1$–$X3$ and $X6$–$X11$, which have a strong correlation with the outcome Y (the corresponding pairwise correlation coefficients $r(Y; Xi)>0.9$). Factors $X4$–$X5$ with low correlation have been excluded from the causal base as statistically insignificant.

Table 7

Initial data for building the causal relationship model between the dependent variable Y (CO_2 Emissions) and independent variables Xi, i=1,...,11 [26–29]

Indicators	Designation	Year									
		2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
CO2 emissions, thousand tons	Y	1511.9	1442.3	1409.9	1371.5	1397.2	1065.8	965.3	544.2	836.4	544.2
Greenhouse gas emissions intensity (tons CO_2 per RPKM)	$X1$	0.0776	0.0767	0.0752	0.0750	0.07591	0.07471	0.0653	0.0688	0.0640	0.06427
Number of Aircrafts	$X2$	30	30	30	31	32	34	35	34	36	42
Average fleet age, years	$X3$	6.4	5.5	6.8	7.5	8.2	8.3	6.5	5.1	4.7	3.9
Departures, thousands	$X4$	35.6	37.7	39.4	41.6	43.9	44.7	47.5	30.8	47.1	51.8
RPKM, billion	$X5$	11.4	11.67	12.41	12.72	13.6	14.3	14.7	8.1	13.1	15.9
APKM, billion	$X6$	7.45	7.55	7.78	7.81	9.0	9.6	10.4	5.8	10.4	13.2
Average aircraft load factor	$X7$	65.4	64.7	62.7	61.4	66.2	67.1	70.7	71.6	79.4	83.0
Passenger traffic, million people	$X8$	3.68	3.77	3.86	3.75	4.19	4.32	5.12	3.7	6.6	7.4
Freight traffic, thousand tons	$X9$	23.8	19.0	16.6	16.6	19.9	20.0	13.9	13.9	18.8	14.0
Ton-kilometers performed, million	$X10$	753	748	762	767	771	783	737	731	752	746
Fuel consumption, thousand tons	$X11$	180.6	183.0	188.6	189.3	218.2	232.7	252.1	170.4	261.9	319.9

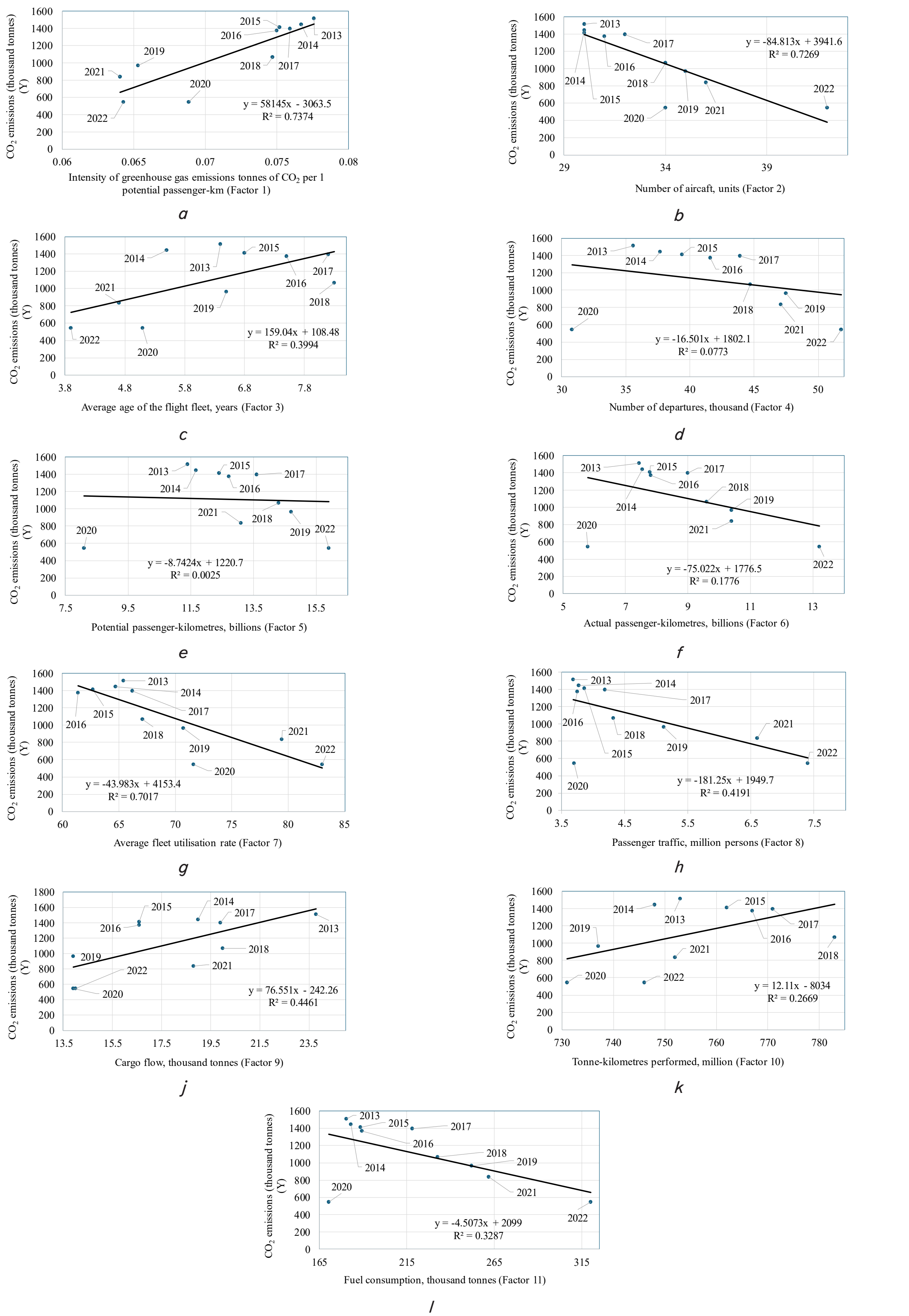


Fig. 5. Scatter plots displaying pairs of values "dependent variable Y – factor variable Xi" – (Y; Xi), i=1,...,11: *a* – emission intensity; *b* – number of aircraft; *c* – average age of the fleet; *d* – number of departures; *e* – marginal passenger-kilometers; *f* – actual passenger-kilometers; *g* – average fleet load factor; *h* – passenger traffic; *i* – cargo traffic; *j* – actual cargo carried; *k* – volumes of fuel consumed

4. The analysis of multicollinearity among the variables $X1$–$X3$ and $X6$–$X11$, to identify mutually independent factors affecting the outcome variable Y in the multiple regression model, was conducted using regression-correlation analysis.

The analysis of pairwise correlation coefficients for factors $X1$–$X3$ and $X6$–$X11$ revealed dependencies between some of them, where the corresponding $r(Xi; Xk)>0.7$. To address multicollinearity, the approach of discarding the variable Xk with high correlation was applied. Consequently, factors $X6$ and $X7$ were excluded from the causal base.

5. The construction of linear multiple regression models for systems of independent factors was carried out using econometric modeling methods.

Combining the remaining factors $X1$–$X3$ and $X8$–$X11$ into sets of three linearly independent factor systems allowed for the construction of four linear multiple regression models:

$$Y1=-2670.97+53430.78X1+0.7743X3-0.7572X9, \quad (1)$$

$$Y2=3571.073-77.2943X2+7.4958X3+7.1333X9, \quad (2)$$

$$Y3=4290.409-223.906X8+ +19.79869X9-3.18667X10, \quad (3)$$

$$Y4=2313.301+5.988522X9+ +0.343031X10-6.70585\,X11. \quad (4)$$

The unknown parameters of the regression models $Y1$–$Y4$ were obtained using the method of least squares, and the adequacy of the models was assessed using the Fisher criterion:

$$F1\geq F2\ (\alpha;\ k1;\ k2), \quad (5)$$

where $F1$ – calculated value of the criterion,

$F2$ – tabular value of the criterion,

α – chosen significance level ($p=1-\alpha$ – probability),

$k1=m$ and $k2=n-m-1$ – degrees of freedom,

$n=9$ – number of observations,

$m=3$ – number of independent factors.

The calculated adequacy indicators for regression models (1)–(4) are summarized in Table 8.

Table 8

The system of adequacy indicators for regression models

Model of regression	R^2	$F1$	Probability	$F2(0.05; 3; 5)$	Quality of model
Y_1	0.8347	8.4132	$\alpha=0.05$ ($p=0.95$)	5.409451	High
Y_2	0.9512	32.4542			Very high
Y_3	0.9341	23.6066			Very high
Y_4	0.9514	32.6137			Very high

The calculated value of the Fisher criterion for all regression models $Y1$–$Y4$ exceeds the tabulated value, indicating that all models are adequate. Moreover, the coefficient of determination R^2 approaches 1, which signifies a high quality of the constructed models.

Thus, it is possible to conclude that the most significant impact on CO_2 emissions from civil aviation in Republic of Kazakhstan is exerted by cargo and passenger transport volumes, and consequently, by the volume of fuel consumed. Therefore, among the measures for reducing the carbon footprint of international aviation, ICAO anticipates the greatest effect from transitioning to “cleaner energy sources” (Fig. 2), specifically:

1. The sustainably produced types of aviation fuel (LTAG-SAF) that meet the LTAG parameters include:

a) biomass-based fuels (plant oil crops, lignocellulosic energy crops, starchy energy crops, sugary energy crops);

b) waste-based fuels:

1) solid waste – plant residues, municipal solid waste, forestry residues;

2) liquid waste – wastes and by-products from the production of fats, oils, and greases (FOG);

3) gaseous waste – CO_2 emissions from the production of ethanol, ammonia, iron, steel, and cement;

c) atmospheric CO_2-based fuels.

2. Types of aviation fuel with lower carbon content that meet the LTAG parameters (LTAG-LCAF) – petroleum-based fuel with a carbon intensity from production to delivery of <80.1 gCO_2e/MJ, using technologies and best practices in reducing greenhouse gas (GHG) emissions.

3. Non-blended fuels containing cryogenic hydrogen (LH2) [15].

The transition of aviation to “cleaner energy sources” is inevitable because:

1. Firstly, the 39th ICAO Assembly introduced the Global Market-Based Measure (GMBM) in the form of CORSIA. According to this, ICAO member states that have committed to participating in CORSIA must ensure that CO_2 emissions are limited to 85 % of the 2019 level, particularly through the use of cleaner energy sources (including SAF and LCAF – sustainably produced petroleum – based fuels with a reduced carbon footprint) at a level of at least 5 % by 2030 [19]. Aircraft operators that do not meet the requirement to reduce the carbon footprint of international cargo and passenger transportation are subject to compensatory obligations, which can be met by purchasing carbon credits (emission allowances) through the Emissions Trading System (ETS) or by paying compensation obligations for CO_2 emissions.

Compensatory obligations are calculated based on:

a) an airplane operator’s offset requirement=[% sectoral×(an airplane operator’s emissions covered by CORSIA in a given year×the sector’s growth factor in the given year)]+[% individual×(an airplane operator’s emissions covered by CORSIA in a given year×that airplane operator’s growth factor in the given year)];

b) sector’s growth factor from 2021 through 2023=(total emissions covered by CORSIA in the given year–total emissions covered by CORSIA in 2019)/total emissions covered by CORSIA in the given year, and the sector’s growth factor from 2024 through 2035=(total emissions covered by CORSIA in the given year–85 % of total emissions covered by CORSIA in 2019)/total emissions covered by CORSIA in the given year [19];

c) airplane operator’s growth factor from 2033 through 2035=(the airplane operator’s emissions covered by CORSIA in the given year–85 % of the airplane operator’s emissions covered by CORSIA in 2019)/the airplane operator’s emissions covered by CORSIA in the given year;

d) % sectoral=(100 %–% individual);

e) % sectoral and % individual will be applied as follows:

1) from 2021 to 2023: 100 % sectoral and 0 % individual;

2) from 2024 to 2026: 100 % sectoral and 0 % individual;

3) from 2027 to 2029: 100 % sectoral and 0 % individual;

4) from 2030 to 2032: 100 % sectoral and 0 % individual;

5) from 2033 to 2035: 85 % sectoral and 15 % individual [19].

It is worth noting that participation of states in the experimental phase (2021–2023) and the first phase (2024–2026) of CORSIA is voluntary. Starting from January 1, 2027, the second phase of CORSIA will be mandatory for all states [20].

2. Secondly, the European Parliament approved a reform of the Emissions Trading System (ETS) in April 2024, which includes the elimination of free carbon emission allowances for the aviation sector by 2026. This means that if aircraft operators do not meet the carbon footprint reduction requirements, they will not be able to use free carbon allowances to offset their compensatory obligations. Consequently, this will lead to increased financial costs and a loss of competitive position in the international cargo and passenger transport market.

3. Thirdly, at the ATAG1 Global Sustainable Aviation Forum held during COP28, a new 5-level airport certification program was introduced. This program marks a significant shift in the reduction of carbon emissions by airports, including:

1) achieving and maintaining a net zero carbon balance in accordance with the ISO Net Zero Guidelines (Scope 1 and Scope 2);

2) mapping and reporting for all other emissions (Scope 3), and so on.

Some governments, aviation associations, and individual airlines have announced ambitious goals regarding the share of SAF usage in the near and long-term future. However, the practical feasibility of these goals remains uncertain due to several unresolved issues with SAF, including: high cost: SAF is, on average, 2–5 times more expensive than conventional jet fuel (CJTF), and experts do not expect significant price reductions in the near future; limited supply: SAF currently accounts for only 0.1 % of all aviation fuel, and the prospects for expanding production are uncertain and do not meet forecasts; limited international technical certification: there is a lack of comprehensive international technical certification and sustainability certification for SAF according to CORSIA criteria; lack of ICAO methodologies: There are no ICAO methodologies for assessing the eco-economic efficiency of SAF. These factors pose challenges to the widespread adoption and implementation of SAF in the aviation industry [31].

It should be noted that the working document of the Third ICAO Conference on Aviation and Alternative Fuels (CAAF/3) titled "Metrics and Forecasts for Potential Quantitative Targets for Cleaner Energy Sources in International Aviation," held from October 20–24, 2023 [31], outlines several possible metrics for the eco-economic efficiency of SAF. However, their application for forecasting and scenario building will only be feasible once airlines provide their reports for 2024. Therefore, given the existing information constraints, for developing scenarios for the transition of the Air Astana Group to next-generation fuels, it is possible to use the annual MRV (Monitoring, Reporting, and Verification) data, applied model (1), and employed "What-If Analysis" and "What Is Needed For" scenario forecasting methods to develop possible scenarios for the development of the studied system of factor and performance indicators for the years 2030–2050 (Table 9).

In accordance with a recent resolution from the Association of Asia-Pacific Airlines, the Group has set a goal to achieve a 5 % blending rate of sustainable aviation fuel with conventional fuel by 2030. This target aligns with the decarbonization scenario forecasts provided by the Air Transport Action Group (ATAG) in the Waypoint 2050 Report [32].

Table 9

The results of the scenario modeling for the carbon footprint of Air Astana Group's aviation operations for the years 2030–2050

Indicators	Scenario 1 (Optimal)			Scenario 2 (Nominal)			Scenario 3 (Pessimistic)		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
The percentage of SAF and LCAF blending with fossil fuel	5	12	25	3	8	20	3	6	15–17
Greenhouse gas emission intensity (tons of CO_2 per passenger-kilometer)	0.0546	0.0473	0.0417	0.0578	0.0517	0.0462	0.0604	0.0547	0.049

5. 4. Development of a simulation model for constructing an algorithm for the transition of civil aviation to new generation fuel

However, it should be noted that the international race towards the adoption of SAF and leadership in its production has already begun [33]. In 2023, the increase in SAF volumes became possible due to the commissioning of new renewable fuel production facilities, as well as the expansion of existing production capacities in North America, Europe, and the Asia-Pacific region [34].

As part of a strategic partnership with PetroChina International Republic of Kazakhstan for the supply of Jet A-1 aviation fuel, Air Astana Group plans to import SAF directly from China [30]. However, as stated in [35], Republic of Kazakhstan has a sufficient raw material base for its own production of SAF [35].

1) non-standard grain, which, through deep processing into ethanol using fermentation and distillation technologies, can be used as raw material for SAF production via Alcohol-to-Jet (ATJ) technology.

2) agricultural waste, specifically:

– biomass rich in fats and oils can be processed into SAF through hydroprocessing;

– biogas obtained from the anaerobic digestion of agricultural waste can be used to produce syngas, which is then processed into SAF;

– syngas obtained from agricultural waste using the Fischer-Tropsch (FT) method can also be used to produce next-generation aviation fuel;

– organic waste (as part of municipal solid waste). The synthetic gas (syngas) produced from its gasification can be further processed through the Fischer-Tropsch method to synthesize liquid hydrocarbons, which can then be refined into high-quality aviation fuel;

– energy crops (such as sorghum, miscanthus, amaranth, and others that are drought-resistant and can grow in low-fertility soils). The high biomass yield from these crops can be used to produce biogas, which can, in turn, be utilized for the production of aviation biofuel;

3) flue gases (such as those from ArcelorMittal Temirtau, Aktobe Ferroalloy Plant (part of Eurasian Resources Group, ERG), and others) can be hydroprocessed to produce refined hydrocarbons, which can then be used to produce fuel that meets aviation standards.

The production of next-generation aviation fuel in Republic of Kazakhstan will ensure compliance with the country's carbon-neutral growth commitments, enhance the attractiveness of Republic of Kazakhstan's airports for international carriers, and allow the domestic aviation industry to meet international service quality standards [35].

However, Republic of Kazakhstan's airports will need to focus on establishing refueling infrastructure that is accessible and suitable for the distribution of SAF. It is essential to develop effective logistics chains for transporting SAF from production sites to airports, ensuring infrastructure for transportation and storage that is compatible with the chemical composition of SAF and LCAF. Equally important is the certification of SAF and LCAF, among other considerations.

Thus, the proposed algorithm for transitioning Republic of Kazakhstan's civil aviation to next-generation fuel, as a fundamental basis for developing a Roadmap for the transition of Republic of Kazakhstan's civil aviation to SAF, includes measures for transforming not only the aviation sector but also related industries (Fig. 6).

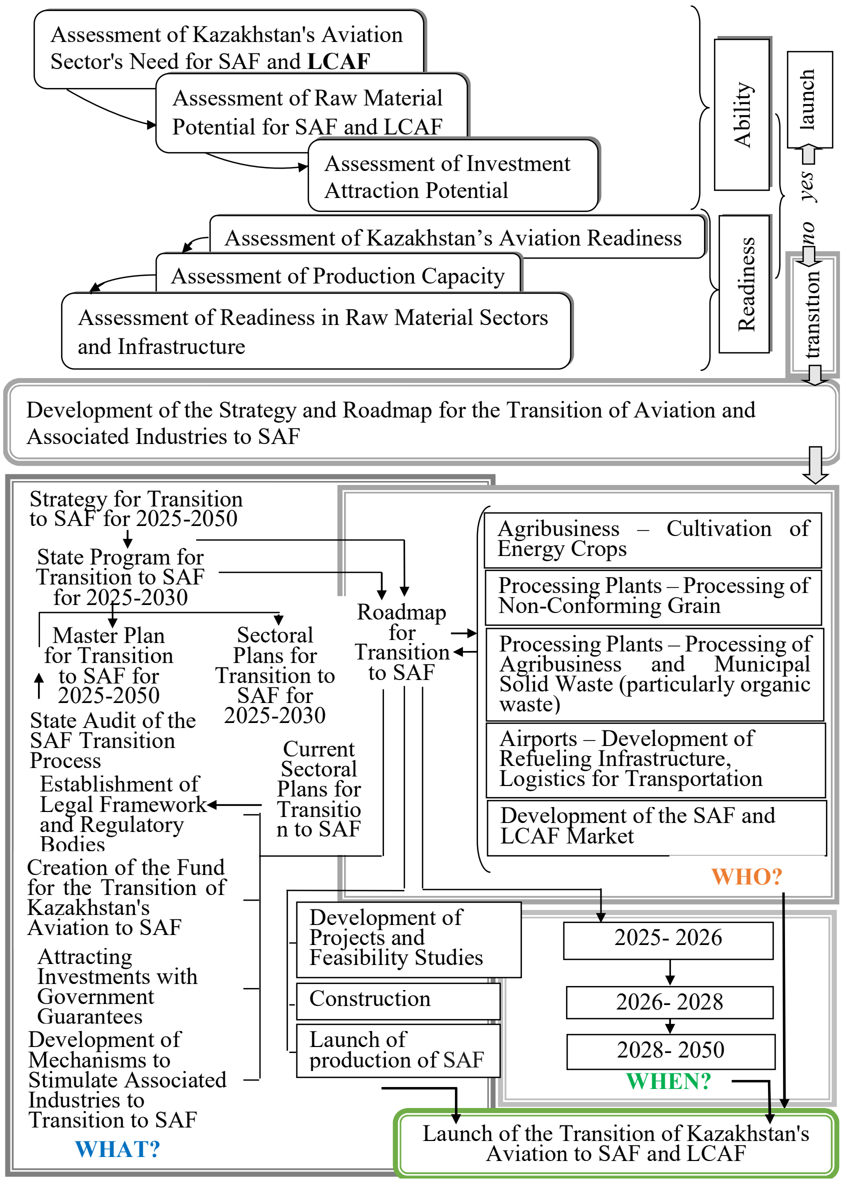


Fig. 6. Simulation model for constructing an algorithm for the transition of civil aviation to new generation fuel

The algorithm is designed in such a way that it clearly answers the questions of what needs to be done, by whom, and when, effectively serving as an Implementation Plan for the Roadmap for the Transition of Republic of Kazakhstan's Civil Aviation to SAF and LCAF.

The practical application of the proposed algorithm will ensure a smooth transition for the Republic's civil aviation and associated industries to the production of new-generation fuels, considering the anticipated development pace of Republic of Kazakhstan as an aviation transportation hub.

6. Discussion of the results of the study on the development of an algorithm for the transition of civil aviation to new generation fuel

The results of this work confirm the necessity and feasibility of decarburization of civil aviation by switching to new generation fuel, which was also emphasized by a group of leading researchers [5–11]. In work [5], the researchers focused on possible options for reducing carbon emissions by aviation. However, their plausibility and feasibility are not sufficiently substantiated due to the lack of a clear plan for the transition of aviation to the use of SAF. The research results presented in [6] are more convincing, since they consider in sufficient detail each of the possible ways to implement aviation decarburization, but are not of an applied nature. This shortcoming is taken into account by the researchers in [7–9], but the researchers focused only on the potential and readiness of aviation for the fuel transition. The authors do not outline the policy and clear measures for its implementation. In the article [10], the researchers consider international and national policies for the transition of aviation to SAF, but do not offer an algorithm for the transition of civil aviation to the new generation fuel, which, in our opinion, is a significant omission that complicates the development of strategic documents and, accordingly, the adoption of measures to decarbonize air transport.

Unlike [5–12], these studies are based on quantitative indicators, retrospective and forecast data of ICAO for the period up to 2050 (Fig. 2), which ensured more realistic results. Since LTAG [16] is built taking into account CO_2 emissions and the readiness of aviation to reduce its carbon footprint (Fig. 2), in order to form forecasts and develop a plan of measures to reduce it by civil aviation of Kazakhstan, the volume of CO_2 emissions by the Republic's aviation (Fig. 3), as well as the key factors influencing its dynamics, were studied. In particular, the quantitative and qualitative composition of airliners in the air fleet of airlines of Kazakhstan (Table 1), as well as their age by aircraft models (Table 2), which were visualized in Fig. 4, *a*, *b*. It was found that the leader both in the number of aircraft and in their "newness" is the country's largest carrier, Air Astana Group. The average age of the company's airliners in 2022 was 3.9 years. At the same time, the Air Astana fleet consists mainly of Airbus A320 and Airbus A321 aircraft, which are fuel-efficient and environmentally friendly. Given the leading positions of Air Astana Group in the Kazakhstan air transportation market, it was decided to use the company's data as a basis for the study. Based on the data obtained (Tables 3–7), the key factors influencing the carbon footprint of air transportation were identified (Table 7). Having prioritized them (Fig. 5–15), models (1–4) of cause-and-effect dependencies between the resulting feature Y (CO_2 emissions) and factor features Xi, i=1, ..., 11 (these dependencies have no analogues in the literature) were constructed. Unknown parameters of regression models $Y1$–$Y4$ were obtained using the least squares method, the adequacy of the models was assessed using the Fisher criterion (5). The results of checking the adequacy of regression models (1)–(4) are summarized in Table 8. The calculated value of the Fisher criterion for all regression models $Y1$–$Y4$ is higher than the tabular one, which means that all models are adequate. Moreover, the value of the determination coefficient R^2 approaches 1, which indicates the high quality of the constructed models.

Thus, it has been proven that the greatest impact on the volume of CO_2 emissions by civil aviation in Kazakhstan is exerted by the volumes of cargo and passenger transportation and, accordingly, the volumes of fuel consumed. Therefore, among the measures to reduce the carbon footprint, the most effective is expected to be the transition of aviation to SAF.

Given the existing information limitations, in order to build scenarios for the transition of Air Astana Group to new generation fuel, based on the annual MRV (monitoring, reporting and verification) data using model (1) and using the methods of situational forecasting "What-If Analysis" and target modeling "What Is Needed For", in this study have developed possible scenarios of the carbon footprint of Air Astana Group for 2030–2050 taking into account the percentage of SAF and LCAF blending with fossil fuels (Table 10).

It has been proven that the transition of civil aviation to SAF and LCAF requires a number of measures, in particular: creating a refueling infrastructure accessible and suitable for SAF distribution, developing effective logistics chains for delivering SAF from production sites to airports, providing infrastructure for storing SAF and LCAF compatible with the chemical composition, etc. The clarity and timeliness of their implementation is possible only if there is an algorithm for the transition of civil aviation in Kazakhstan to a new generation fuel, which should include measures to transform not only the aviation industry, but also related industries. Since ICAO and other international organizations in the field of aviation have not yet proposed methodological recommendations for building this algorithm, and they are not found in the results of scientific research, in this research proposed a simulation model for building an algorithm for the transition of civil aviation and related industries to SAF and LCAF. This simulation model has no analogues.

The main limitation in this study should be recognized as the lack of full-fledged information support for the environmental component of the activities of airlines in Kazakhstan, which has become a barrier to studying the progress and factors influencing the reduction of the carbon footprint of civil aviation in the Republic of Kazakhstan. According to the CORSIA scheme, all air carriers without exception are required to report on the achievement of sustainable development goals. Ignoring this requirement threatens Republic of Kazakhstan airlines with the payment of compensation obligations to reduce carbon emissions, since in the absence of reports with verified data, it is almost impossible to prove progress in reducing CO_2 emissions in previous years and to digitalize environmental control [35–39], the lack of progress in which is seriously noticeable today. This study can be developed in terms of creating an air cargo hub in Republic of Kazakhstan, prospects for the development of infrastructure projects, in particular airfield solutions, construction of airports and oil storage facilities for aviation, production of aviation biofuel, etc.

7. Conclusions

1. It was stated that aviation remains heavily dependent on fossil fuels and therefore remains a major polluter in terms of carbon emissions. It was highlighted that the 41st ICAO Assembly adopted a collective long-term ambition goal (LTAG) to achieve carbon neutrality in international aviation by 2050. To achieve this, ICAO has implemented the CORSIA scheme, which is designed to ensure carbon-neutral growth in international aviation. And primarily through the transition to sustainable aviation fuel (SAF). Based on projected calculations of qualitative and quantitative indicators, this will reduce the carbon intensity of aviation fuel by about 80 % by 2050 compared to the fossil fuels currently used.

2. It has been established that international transportation by airlines of Republic of Kazakhstan is carried out on 103 air routes to 27 countries. At the same time, CO_2 emissions by civil aviation of the Republic of Republic of Kazakhstan per year, according to the ICAO document: CORSIA Central Registry (CCR): Information and Data for Transparency, amount to more than 800 thousand tons. It has been substantiated that the number of international routes as determines the carbon footprint of aviation not so much by the condition of Republic of Kazakhstan's aircraft. According to the conducted researches as of 01.01.2024, the average age of the aircraft fleet of Republic of Kazakhstan was 11.2 years, which indicates an average level of readiness of Kazakhstan's civil aviation to switch to "clean" aviation fuel. Emphasis is also placed on the readiness of related industries for the transition of Kazakhstan's civil aviation to alternative types of aviation fuel (SAF and LCAF). The calculations show that the transition to next-generation fuel requires large-scale investments in production capacity, cost reductions throughout the SAF production chain, and the allocation of funds for ASTM certification.

3. Key factors influencing the carbon footprint of civil aviation were identified using data from the leading airline in Republic of Kazakhstan and Central Asia, Air Astana Group. A mathematical model was developed to analyze the dependency of the resulting indicator Y (carbon footprint level) on a set of factor indicators Xi, identified through the examination of the company's annual and integrated reports for the period 2013–2022. The presence of multicollinearity among the set of independent factors influencing the result indicator Y was proven. Attention was focused on possible options for reducing aviation carbon emissions in the short, medium, and long term. It was argued that transitioning to

new generation fuels appears to be the most realistic method for reducing the carbon footprint of civil aviation at the current stage.

4. It has been emphasized that despite Kazakhstan's statement of readiness to switch to low-carbon fuel, neither the Strategy nor the Roadmap for the transition of Kazakhstan's civil aviation to SAF and LCAF have been developed to date. This significantly complicates attracting investment and fulfilling the commitments made to reduce the carbon footprint of the republic's aviation. A simulation model of the algorithm for the transition of Kazakhstan's civil aviation to new-generation fuels has been proposed, which can serve as a fundamental basis for creating a Roadmap for the transition of Kazakhstan's civil aviation to SAF and LCAF, since it provides answers to such important questions as: who, what and when. That is, it acts as a kind of coordinator of the actions of those interested in implementing the transition of civil aviation to new-generation fuel. This simulation model has no analogues. Its practical application will accelerate the transition to SAF and LCAF in the coming years and thereby maintain the competitive positions of Kazakhstan's civil aviation in the global air transport services market.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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