UDC 330.322:338.2:502.131.1:629.7
JEL Classification: O32, E22, Q01, Q56, L93
DOI: 10.15587/2706-5448.2025.347822

Viktoriia Prokhorova,
Oleksandra Mrykhina,
Orest Koleshchuk,
Krystyna Slastianykova,
Roman Paraniuk,
Darii Koleshchuk

CIRCULAR-ORIENTED ECONOMIC ASSESSMENT OF INNOVATIONS USING DIGITAL TWIN TECHNOLOGY FOR AN AIRCRAFT HYDRAULIC SYSTEM

The object of this research is the set of processes involved in the economic evaluation of innovative technologies under circular-economy conditions. The subject concerns the methods and models used to assess their economic efficiency. This is illustrated through the digital twin of an aircraft hydraulic system. The research substantiates a system of techno-economic indicators for evaluating an innovative technology. It also prepares the initial scenario data needed for modelling its development under different levels of circular-practice implementation. Three scenarios – pessimistic, baseline, and optimistic – are modelled. This is followed by an analysis of cash flows and discounted efficiency indicators (NCF, payback period, NPV, IRR, PI) and a comparative assessment of techno-environmental parameters. The sensitivity of the results was analysed using the derivative-based method to determine the influence of the key factors.

The modelling of indicators with circular practices showed that even in the pessimistic scenario the technology project is still attractive for investments. For example, when CAPEX = 1.59 million USD, the project makes NCF = 808.7 thousand USD. The efficiency indicators (NPV = 2.34 million USD, IRR = 42%, PI = 2.47) confirmed that the project is good to do. The baseline and optimistic scenarios demonstrated that NPV can reach 2.75–2.95 million USD, IRR can be 43–48%, and PI can be 2.59–3.10. In this situation, the payback period becomes almost 1.57 years. Using circularity factors makes the discounted cumulative cash flow positive from year 2–3. Without circularity, it becomes positive only at the end of year 3.

The sensitivity analysis proved how strong the circularity influence is. When NCF goes down by 20%, NPV becomes 1.35 million USD and IRR becomes 25%. When NCF goes up by 20%, NPV grows to 4.15 million USD and IRR grows to 56%.

An analysis of NPV derivatives was also done. The results showed that the marginal effect of early cash flows is almost two times bigger than the effect of later cash flows, with the CAPEX gradient being negative (–1). This allowed to say that fast income creation is very important in the early stages of the project.

Keywords: *circular economy, investment attractiveness, capital-intensive innovations, financial sustainability of innovations, strategic investment.*

Received: 14.10.2025
Received in revised form: 06.12.2025
Accepted: 22.12.2025
Published: 29.12.2025

How to cite

Prokhorova, V., Mrykhina, O., Koleshchuk, O., Slastianykova, K., Paraniuk, R., Koleshchuk, D. (2025). Circular-oriented economic assessment of innovations using digital twin technology for an aircraft hydraulic system. Technology Audit and Production Reserves, 6 (4 (86)), 31–45. https://doi.org/10.15587/2706-5448.2025.347822

1. Introduction

In today's conditions of global competition and the spread of environmental challenges, the key task of economic development of countries around the world is to simultaneously ensure innovativeness, financial efficiency and environmental sustainability of technologies. In view of this, the economic evaluation of capital-intensive innovations becomes particularly meaningful. Decisions on their investment are made on the basis of forecasting long-term costs and revenues. However, in practice, the use of evaluation approaches focused mainly on obtaining financial results on the principle of "here and now" often dominates. Therefore, such aspects as reducing the level of resource intensity of technologies, extending the life cycle of their components, optimizing waste management and other social and environmental effects are often ignored. The integration of circularity principles into the system of economic evaluation of innovations should be considered as a mandatory element of modern economic analysis, and not just as its complement. Otherwise, a "methodological gap" will form between the environmental and financial and investment arguments, which will underestimate the attractiveness of developments. This is particularly evident in the case of complex engineering technologies. In particular, in aviation systems, where equipment downtime due to failures of individual components can reach up to 30% of the operating time [1]. Each hour of downtime leads to significant financial losses – fines, canceled flights and, as a result, loss of potential income. An example of this type of technology is digital twins (DT), which, thanks to predictive maintenance, are able to reduce the number of emergency stops, extend the life of expensive components, etc. In turn, this helps reduce repair costs. It is for such technologies that the problem of substantiating economic feasibility taking into account the principles of circularity is significant. After all, DTs require significant initial investments. They have a complex multi-component cost structure, which, accordingly, makes it difficult to determine the expected efficiency of their implementation.

Under the above conditions, there is a need not only to adapt existing methods, but also to create a comprehensive methodological approach that would allow for the combination of technical, environmental and cost components, including long-term effects of technology operation, and taking into account the principles of the circular economy. Otherwise, the economic justification risks remaining fragmentary. This will reduce its practical value when making management and investment decisions.

The development of digitalization and the circular economy requires new approaches to assessing the economic efficiency of innovative technologies. At the same time, in scientific works, these areas are mostly developing in parallel, which complicates their integration into a single methodology.

In modern research, more and more attention is paid to the economic aspects of the DT implementation. In particular, a systematic review [2] summarizes the existing scientific research in the field of architecture, engineering, construction, demonstrating the DT potential in reducing costs and increasing efficiency. In the work [3], scientists focus primarily on modeling the economic benefits of production systems. Whereas the authors of the publication [4] propose a different plane – a structured framework for investment decisions, built on the comparison of revenues and costs. These studies form a theoretical basis for further assessment of the economic feasibility of the DT implementation. At the same time, their limitation is the focus on financial and economic indicators, without taking into account the long-term effects of circularity. This narrows the possibilities of using the obtained results in the context of sustainable development.

Further development of the topic is presented in the works [5–7], where the authors investigate the relationship between DT and the circular economy. In particular, in [5] a thorough systematization of scientific sources on this topic was carried out. Based on this, a conceptual model of the DT use in closed production cycles was proposed. At the same time, such a model is mostly declarative in nature; it is not accompanied by formalized economic tools for assessing its effectiveness. This, in turn, narrows the possibilities of its practical use when making investment decisions. On the other hand, in [6] the emphasis is shifted towards analyzing investment in the field of renewable energy (while DT is considered as an auxiliary optimization tool). The economic effects of their implementation are estimated indirectly. The authors did not single out the DT contribution to the formation of the life cycle cost of technologies. In [7] the potential synergy between DT and the Internet of Things is demonstrated using the example of energy projects. In this publication, the analysis is focused mainly on technical and organizational aspects. The economic justification of circular effects remains fragmentary. The studies presented in the above publications confirm the promising potential of digital technologies for sustainable development. It remains an open question whether they do not form a holistic methodology for economic assessment. Obviously, an assessment is needed that would take into account both the innovativeness and circularity of technological solutions. A significant body of research concerns the analysis of the economic results of circular strategies at the macro level [8–10]. Thus, in [8] the authors convincingly demonstrate the long-term economic feasibility of such strategies based on panel data, and in [9] they provided empirical evidence of the positive impact of circular approaches on the economic development of EU countries. In [10] the scientists focused on the role of economic, technological and environmental factors. They considered these factors as key drivers of circular transformations. Collectively, these works confirm the strategic importance of the circular economy as one of the factors of long-term development. At the same time, it should be noted that these studies are of a generalizing nature and are focused primarily on systemic and institutional effects. As a result, the economic results of the implementation of specific innovative technologies at the micro level remain outside the scope of the analysis. For example, the DT impact on the formation of long-term efficiency in the conditions of a circular economy is practically not considered in such works. This complicates the use of the conclusions obtained to substantiate management decisions.

In the Ukrainian scientific discourse, it is worth noting the works [11–13], which have developed methodological approaches to assessing the impact of technological changes on the activities of business entities. In particular, in work [11], a toolkit for measuring the parameters of technological changes and assessing their determining role in the context of the economic sustainability of enterprises is proposed. In the study [12], intellectual and innovative technologies are considered in their relationship with sustainable development, while in [13], the dynamics of economic progress of enterprises under the conditions of technological transformations are analyzed. Without a doubt, these works are of great importance for the formation of a system of indicators for the economic assessment of innovations. They also create an important methodological basis for further research. At the same time, their focus is usually on general processes of technological changes, linear models of enterprise development, etc. As a result, the issue of using DT as a separate innovation tool in circular economy models remains beyond consideration. Therefore, this limits the possibilities of practical implementation of the proposed approaches for evaluating modern digital technologies.

A separate group is formed by studies covering the development of technical and economic methodologies for evaluating innovations [14–17]. Thus, in the work [14], improvement of investment approaches through the concept of NPV-consistency is proposed. This allows for a more accurate comparison of costs and expected revenues from the implementation of projects. In the study [15], probabilistic models for assessing efficiency under conditions of uncertainty were developed, which is essential, given the high level of risk of innovative technologies. The authors of the publication [16] carried out a systematic review of modern directions of technical and economic analysis. In [17], attention is focused on the specific difficulties of evaluating carbon capture and utilization (CCU) technologies at the early stages of their development. It can be argued that the above studies significantly expand the tools for economic evaluation of innovations, since their application is mostly based on classical approaches focused on linear models of the life cycle of technologies. As a result, the specifics of the circular economy (effects of asset life extension, component reuse, etc.) do not receive proper analytical coverage. In addition, DT, as a complex innovative technology, is practically not considered within the framework of these methodologies. Accordingly, this somewhat limits their suitability for assessing the economic efficiency of modern digitally-oriented solutions. Applied and interdisciplinary studies [18–21] significantly deepen the understanding of the possibilities of practical implementation of circular solutions in various sectors of the economy. For example, in the study [18], scientists carried out a technical and economic assessment of integrated processes in palm oil production aimed at increasing the efficiency of resource use within the framework of a circular economy. In the article [19], the key barriers and possible routes for the implementation of circular principles in industry are analyzed (this demonstrates the important applied value for the transformation of production systems). The work [20] deserves special attention, which proposes a comprehensive approach to the integration of economic and environmental aspects of the functioning of biorefineries. In the work [21], the marketing dimensions of the development of circular solutions are considered. In general, these studies illustrate the potential of circular strategies in various industries. However, their focus is mainly on industry-specific, process-oriented solutions. As a result, DT, as a universal innovative technology capable of systematically influencing the economic models of enterprises, does not become the subject of systemic analysis.

Additional practical context is formed by studies [22–31]. They summarize numerous cases of implementation of circular models in different industries and regions. In particular, in [22], scientists analyzed the integration of circular economy principles into business strategy within the framework of EU–LAC cooperation. In [23], practical aspects of implementing circular approaches in the paper and retail industries were considered. The effectiveness of using digital tools to increase the productivity of production processes was demonstrated in [24]. In [25], the possibilities of the impact of circular measures on the development of digital startup projects were highlighted. In [26], the relationship between economic growth and the transition to a circular economy was investigated. The authors of this publication proposed the concept of post-growth circularity as more consistent with the principles of sustainable development. Of particular note is the publication [27], in which scientists conducted a critical review of existing circularity metrics and also showed the possibilities of measuring real progress in achieving sustainable development goals. In [28], the relationship between economic complexity and the level of circularity was analyzed. An important addition is the study [29], devoted to assessing the level of economic circularity in EU countries, as well as the paper [30], which clarified the theoretical foundations and practical limits of implementing a circular economy (including its connection with the processes of cyclicality, entropy, etc.). The publication [31], which authors proposed approaches to assessing the environmental attractiveness of the country's investment and innovation environments, is also distinguished by its scientific significance in the specified context. In general, these studies significantly expand the empirical base, demonstrating the variety of practical approaches to implementing the principles of a circular economy. However, they are fragmentary in nature and focus mainly on individual sectors, institutional levels, general indicators of circularity, etc. In this regard, there is no systematic methodological approach to the DT economic evaluation as an innovative technology in the context of a circular economy.

The generalization of the results of the analysis of scientific sources indicates the presence of a scientific and practical gap – the lack of a holistic methodological approach to the economic evaluation of innovative technologies (in particular, DT) taking into account the principles of the circular economy.

The above has determined *the aim of research* – to substantiate the methodological support for the economic evaluation of innovative technologies based on the principles of the circular economy (using the example of the DT technology of the aircraft hydraulic system).

To achieve the set aim, it is necessary to perform the following tasks:

- to characterize the innovative technology – the object of economic evaluation;
- to substantiate the system of technical and economic parameters for evaluating the technology and generate scenario data for its development on the principles of circularity;
- to model scenarios for the development of technology in a circular economy, analyze cash flows and the discounted efficiency of its implementation;
- to assess the sensitivity of indicators of the effectiveness of technology implementation taking into account circular practices and determine the sensitivity of results using the derivative method;
- to substantiate the controversial provisions and key limitations of research of the economic evaluation of technology.

2. Materials and Methods

The object of research is the processes of economic evaluation of innovative technologies in the context of a circular economy. *The subject of research* is methods and models for evaluating the economic efficiency of innovative technologies taking into account the principles of circularity (using the example of the DT technology of the aircraft hydraulic system).

The methodological basis of this work is the author's model of the system of economic evaluation of innovations. It combines the analysis of technical parameters of reliability, operating costs, carbon footprint of the technology, as well as financial indicators of the efficiency of the investment project. This approach corresponds to modern directions of development of the technical and economic analysis of innovations in the context of sustainable development and circular economy [14–17, 27].

The results of the practical work of the DT technology development group (Lviv Polytechnic National University, Lviv, Ukraine) were used to form the initial data. In addition, generalized statistical and regulatory reference data of the aviation industry (duration of maintenance cycles, failure probabilities, cost of spare parts, labor costs, electricity tariff, specific CO_2 emissions, etc.) were taken into account. Based on these data, the basic values of the variables were determined: failure frequency, downtime and repairs (with and without DT), readiness level, equipment working time fund, margin per hour, etc. *CAPEX*, *OPEX*, tariff, CO_2 price, specific network emissions (EF_{grid}) and parts production (EF_{part}) indicators were also established.

For the economic assessment of the effectiveness of the innovative technology, the scenario analysis method was used, which is a generally accepted tool for assessing investment decisions under conditions of uncertainty [14, 15]. Within the framework of this approach, three scenarios of technology development were modeled – pessimistic, baseline and optimistic, which differ in the level of implementation of circular practices (from their absence to full-scale reuse of components). For each scenario, the following were calculated:

- technical and economic indicators: number of failures, downtime, energy consumption, volume of spare parts reserves, CO_2 emissions, etc.;
- financial indicators: annual costs and savings, net cash flows (*NCF*), payback period, net present value (*NPV*), internal rate of return (*IRR*), profitability index (*PI*), discounted and cumulative cash flows.

Additionally, a sensitivity analysis was performed, which made it possible to determine the impact of variations in key input parameters (*NCF*, *CAPEX*, discount rate, planning horizon) on the integral indicators *NPV* and *IRR* [15, 16]. To deepen the assessment, an approach to analyzing the derivatives of *NPV* for NCF_t, *CAPEX* and r was applied. This made it possible to quantitatively determine the marginal contribution of each parameter [14, 17], and contributed to the assessment of the speed of formation of the economic effect over time.

The environmental dimension of economic efficiency is estimated based on the calculation of CO_2 emissions using the specific carbon intensity coefficients of electricity EF_{grid} and production of components EF_{part}. Also, by monetizing them at a fixed carbon price, which is consistent with modern approaches to integrating environmental effects into the economic evaluation of innovations [27, 29, 31].

The results obtained are analyzed in terms of financial, technical and environmental efficiency, taking into account the principles of circularity. This corresponds to a comprehensive approach to the evaluation of innovative technologies in the context of sustainable development.

3. Results and Discussion

3.1. Characteristics of the innovative technology selected for economic evaluation

To work out the tasks set in this scientific work, an innovative technology developed by a group of specialists from the Lviv Polytechnic National University was used – the aircraft hydraulic system data acquisition system, designed to implement predictive maintenance.

The data acquisition system technology was created in order not only to record the technical parameters of the system, but also to see its state in dynamics and in real time. This also makes it possible to model the behavior of the hydraulic system, predict the failure of its components, etc. The system is necessary for assessing the residual resource of the system and automated generation of reports using artificial intelligence (AI) to support maintenance decisions. Unlike traditional approaches based on periodic analysis of failure statistics, the developed technology integrates continuous collection of telemetric data. This is important because it allows for physical and mathematical modeling of work processes, predictive analytics algorithms based on machine learning, and intelligent data processing modules based on AI. It should be added that the integration of sensor data with a digital model makes it possible to predict the residual resource of each of them, and not only the general technical condition of the system. AI modules automatically analyze the results. They also generate reports on the technical condition. Given the dynamics of the development of modern technologies, it is valuable here that they contain recommendations on the priority of intervention and warnings about critical risks. So, all of the above provides a basis for selective maintenance (i. e., replacing only those elements that are truly exhausted, while preserving the functional ones).

From the standpoint of sustainable economic development, this approach reduces the amount of materials used. It also reduces the need to produce new parts. More practically, this means reducing the burden on supply chains, which directly implements the principles of the circular economy (in particular, it is about extending the life cycle, reusing components, etc.).

It should be emphasized that the system forms historical degradation profiles of each component: they are used for re-certification, re-operation after restoration. Also, to create databases for the secondary market of regenerated aircraft parts. This means that thanks to accurate forecasting, and, accordingly, timely intervention, the number of emergency repairs will be reduced. Obviously, this will reduce the consumption of materials (energy, water, etc.). In addition, it will reduce the volume of hazardous waste (actually those that are generated during disposal).

Thus, there is a situation where a closed material loop is formed as a result: most components are returned to operation after restoration, and not disposed of. This ensures resource-efficient management of material flows. These aspects are fundamentally important, as they confirm the orientation of this technology towards the circular use of resources in the aviation industry.

The implementation of the above-mentioned high-tech system requires a thorough economic assessment of its feasibility. Such an assessment, as a key prerequisite for substantiating management and investment decisions, will allow comparing the costs of development and integration with the projected reduction in operating costs, losses from downtime and material costs, will enable the assessment of the long-term effect, etc.

3.2. Substantiation of the system of evaluation parameters and scenarios for the development of technology in the conditions of a circular economy

For a substantiated economic assessment of the feasibility of implementing the aircraft hydraulics DT, a system of technical and economic parameters should be compiled. Such parameters should comprehensively reflect both the cost and effective aspects of its application.

During the study, it was found that the system should take into account the specifics of the analyzed technology – AI integration (for predicting the condition of components), automated reporting, etc. At the same time, it is important to take into account the factors influencing the extension of the life cycle of parts – in accordance with the principles of the circular economy.

Based on the study of an array of factors of the subject area, an author's system of parameters is proposed (Fig. 1).

A. Reliability and risk parameters
B. Resource parameters
C. Operating cost and downtime parameters
D. Sustainability and circularity parameters
E. Management cost parameters due to technology implementation

Fig. 1. System of technical and economic parameters for evaluating technologies in a circular economy

A. Reliability and risk parameters are among the key ones, as they cover the characteristics that determine the technical stability of the aircraft hydraulic system. Based on the above, and indisputable from a practical standpoint, they make it possible to quantitatively assess the probability of failures, their frequency and accuracy of early detection using DT. The economic meaning of the assessment in this part is to measure the potential reduction in financial losses from the impact of problem factors. A high level of reliability reduces direct costs for restoration (and, accordingly, indirect losses of income from downtime). These parameters can be considered basic for calculating the economic effect of implementing DT. They determine the key benefit – reducing technical and financial risks of operation.

B. Resource parameters reflect the DT ability to extend the life cycle of components of the hydraulic system, which will increase the efficiency of using available material resources. The economic meaning of evaluating this part is to substantiate the potential savings on capital costs due to more accurate management of their use. Resource optimization reduces the level of "freezing" of working capital. It should also be noted that resource parameters make it possible to assess the long-term financial benefit from increasing the efficiency of aircraft operation.

C. Operating costs and downtime parameters include indicators that reflect the cost consequences of servicing the aircraft hydraulic system throughout its life cycle. These parameters are the basis for assessing direct costs (for example, for materials, labor, logistics for repairs, etc.). Also, importantly, financial losses from downtime during troubleshooting. Therefore, the economic meaning of their evaluation is the ability to compare costs under scenarios with and without DT. In turn, this makes it possible to identify potential savings due to reducing the duration of downtime and the frequency of repairs. High maintenance efficiency directly reduces the cost of operation, increasing the profitability of aviation equipment. Therefore, it is obvious that the specified parameters contribute to the measurement of a key component of economic effect – the increase in operational efficiency.

D. The parameters of sustainable development and circularity reflect the environmental and resource-efficient aspects of the DT implementation. This is becoming increasingly important when assessing industrial innovations. Thus, let's demonstrate that they create the prerequisites for a quantitative assessment of the reduction of greenhouse gas emissions. Also, reducing energy consumption and waste volumes, increasing the share of components subject to recovery (or reuse). The above forms the economic meaning of the assessment in this part – determining the long-term benefits from reducing environmental payments, disposal costs and risks associated with regulatory requirements in the field of ESG. The implementation of the principles of the circular economy contributes to reducing the need for primary resources and reducing logistics costs. The proposed group of parameters D makes it possible to take into account not only the economic, but also the environmental efficiency of the technology, which enhances its investment attractiveness.

E. Management cost parameters due to all costs directly related to the design, implementation and maintenance of the aircraft hydraulic system DT technology. Therefore, they include: initial capital investments for development and integration, annual costs for IT infrastructure support, licenses, cloud computing, software maintenance, costs for training personnel to work with the new system, etc. In this part, the economic significance lies in substantiating the total cost of ownership of the technology. Attention should also be paid to determining the break-even point of its implementation. These parameters form the basis for calculating key financial indicators of investment efficiency (*NPV*, *IRR*, payback period, etc.). Thus, management cost parameters make it possible to link the DT technical benefits with the company's real financial obligations.

The study conducted made it possible to identify the basic technical and economic indicators that are part of the above-described groups of parameters of the evaluation system (Table 1).

Table 1

Basic technical and economic indicators of the system of economic assessment of innovative technologies based on the principles of the circular economy (for the aircraft hydraulic system DT implementing predictive maintenance)

Groups of parameters of the evaluation system	Indicators, symbols	Units	Characteristics	Economic interpretation	Data sources
1	2	3	4	5	6
A. Reliability and risk parameters	Probability of component failure, P_f	Probability of failure, [0 ... 100%]/cycle	A metric that reflects the probability of a specific component failing in a given period of time or at a certain interval of operation. It serves as a basis for assessing technical risks and forecasting repair and downtime costs	Expected losses are calculated taking into account the probability of failure and the costs associated with it	AI analysis of component load history and operating modes (telemetry data on pressure, temperature, vibration, on/off cycles; history of actual failures and repairs; trend analysis of material degradation, etc.)
	Frequency of failures, N_{fail}	Number of failures/1000 hours of operation	The number of component failures per 1000 hours of operation or other fixed amount of operation; shows the intensity of failures	Used to calculate the total costs of repairs and downtime, proportional to the number of failures for a certain period	Technical maintenance logs, operation telemetry, repair and incident history, etc.
	Probability of flight delay, P_{delay}	Probability of flight delay, [0 ... 100%]	The proportion of flights delayed due to hydraulic system failures or repairs	Used to estimate expected fines, passenger compensation and reputational losses due to schedule violations	Statistics of airline operational delays, maintenance logs, logistics system analytics, etc.
	Accuracy of AI reports, Q_{report}	Accuracy of AI reports, [0 ... 100%]	The proportion of correct AI system predictions of future failures among all generated reports; demonstrates the reliability of analytics	Determines the effectiveness of preventive maintenance - higher accuracy reduces the costs of incorrect repairs and losses from missed failures	History of generated AI reports, results of their verification by technical personnel, database of actual failures and repairs, etc.
B. Resource parameters	Remaining resource, R_{UL}	Hours/operation cycles to failure	The estimated number of hours or cycles of operation remaining before the failure of a specific component	Used to plan component replacement and estimate savings from maximum use of their resource	Operation telemetry, load and repair history, AI module degradation forecasts, etc.
	Component life cycle, L_{cycle}	Hours/operation cycles to failure	The total number of hours or cycles of operation that a component undergoes from commissioning to the end of its service life	Allows you to estimate the costs of purchasing and replacing components throughout the life cycle and calculate savings from extending it	Manufacturer's technical documentation, repair and replacement statistics, digital twin forecasting results, etc.
	Scrap fraction, R_{scrap}	% of parts that cannot be restored, [0 ... 100%]	The fraction of components that cannot be restored and are subject to disposal after failure	Used to determine material losses, disposal costs and establish the potential for component reuse	Maintenance logs, warehouse reports on write-offs, database of repairs and re-commissioning, etc.
C. Operating cost and downtime parameters	Repair (downtime) time, T_{repair}	Hours	The average duration of restoring the component's operability from the moment of failure to return to operation	Used to estimate financial losses from equipment downtime during repairs, which arise from lost revenue during downtime	Maintenance logs, repair history, telemetry data on downtime
	Repair preparation time, T_{setup}	Hours (supply, diagnostics, etc.)	The average time required to organize repair work – delivery of tools and spare parts, dismantling, diagnostics	Used to estimate additional indirect costs and downtime associated with the start of repair work	Logs maintenance, internal logistics reporting, telemetry of preparatory operations
	Maintenance labor cost, C_{labor}	Mon. units/h	The average cost of paying engineers and technicians for one hour of maintenance and repair work	Used to calculate the costs of carrying out planned and emergency work and compare their economic feasibility	Accounting reporting, time sheets, staff lists
	Parts cost, C_{parts}	Mon. units	The average cost of spare parts and components used to repair or replace hydraulic system components	Used to calculate material costs for maintenance and estimate savings from reducing the number of replacements	Accounting reporting, purchase invoices, technical service database, etc.
	Parts inventory volume, S_{spare}	Mon. units	Cost or quantity of spare parts stored in the warehouse for repair and maintenance	Used to estimate the amount of working capital "frozen" in inventories and the potential for its release through more accurate planning	Warehouse reports, accounting reporting, inventory management system, etc.

Continuation of Table 1

1	2	3	4	5	6
C. Operating cost and downtime parameters	Availability factor, U	Fraction of operating time, [0 … 100%]	The amount of time during which a component or system is in working condition and ready to perform its functions	Used to assess the impact of technical reliability on profitability – a higher availability ratio means more productive time and income	Operation telemetry, maintenance logs, logistics system analytics, etc.
D. Sustainability and circularity parameters	Pump energy consumption, E_{pump}	kWh/year	The amount of electricity consumed by a hydraulic pump during operation over a certain period	Used to measure energy costs and potential cost savings and CO_2 emissions reductions through improved energy efficiency	System telemetry, energy meters, manufacturer's technical documentation, etc.
	Eco-impact cost, C_{env}	Mon. units/year	The total costs due to waste disposal, cleaning of working fluids, payment of environmental fees and compensation for environmental damage	Used to factor environmental costs into total maintenance costs and estimate savings through waste reduction	Accounting and environmental reporting, disposal certificates, environmental payment calculations, etc.
E. Management cost parameters due to the implementation of the digital twin	IT infrastructure costs, C_{IT}	Mon. units (one-time)	The annual costs of supporting software, servers, cloud services, licenses and maintenance of the digital twin	Considered as a component of operating costs and used to estimate the total cost of ownership of a technology	Accounting reporting, contracts with IT suppliers, budgets of IT and maintenance departments, etc.
	Investment in personnel training, I_{train}	Mon. units/year	One-time costs for training engineers and technical personnel to work with the digital twin	Included as part of the initial investment and used to estimate the total cost of implementing a technology	Estimates of training programs, accounting reporting, contracts with training centers or internal budgets, etc.
	Cyber protection costs, C_{cyber}	Units	The annual costs of ensuring information security of the digital twin – protecting data, network infrastructure and user access	Considered as part of operating costs and used to estimate the total cost of ownership and risks of losses from cyber incidents	IT department budgets, contracts with cyber security providers, accounting reporting, etc.

The proposed evaluation system covers key aspects of the technology's functioning (comprehensively: technical, economic, social, and environmental). According to the indicators presented in Table 1, it is possible to successfully assess the level of implementation of the principles of the circular economy in practice. This is obvious, for example, in terms of taking into account the reduction of waste volumes and the extension of the life cycle of components. In addition, the system significantly reflects the factor of reducing the need for the production of new parts (including increasing the resource efficiency of already used parts).

An important feature of this is that, if necessary, the composition of individual indicators within the parametric groups can be changed – this depends on the specifics of the technologies being evaluated. However, the basic logic of building the system itself remains constant.

Before moving on to deeper analytical conclusions, let's consider the technical and economic indicators of the DT of the aircraft hydraulic system that implements predictive maintenance. This will be the basis for further economic assessment of the effectiveness of its implementation. A number of key economic parameters of this technology have been studied under the conditions of the baseline, pessimistic and optimistic scenarios of its development:

- *The baseline scenario* reflects the expected average operating conditions (in particular, this includes stable flight operations, standard maintenance costs, etc.). In this context, it is possible to add that it provides for the implementation of basic elements of the circular economy, which reduces costs throughout the life cycle.
- *The pessimistic scenario* describes a decrease in flight intensity. In this case, attention should be paid to the problems of increasing the frequency of failures and increasing repair and downtime costs. Accordingly, this negatively affects the economic efficiency of the technology. There is practically no effect from circular practices.
- *The optimistic scenario* models conditions with increased flight intensity (and therefore, with reduced maintenance costs). It is valuable to take into account the in-depth level of application of circular approaches. Component renewal and modernization, waste minimization, etc. will allow reducing resource consumption. In turn, this will increase the DT overall cost-effectiveness.

The initial data for the analysis was obtained by generalizing the technical characteristics and operational indicators of hydraulic systems (based on open technical sources, manufacturers' reference materials, etc.). Additionally, average market economic and environmental indicators (costs, prices, CO_2 emission factors, etc.) were used. On this basis, a calculation model was formed. It made it possible to collect sets of initial data for scenarios for implementing the technology of the analyzed DT (Table 2).

Analysis of the data shown in Table 2 showed significant differences between all three scenarios for the development of the aircraft hydraulic system DT technology. This gave rise to a deeper consideration of the conditions for implementing this technology. In particular, the pessimistic scenario assumes increased failure risks ($P_f = 0.10$), a higher frequency of incidents ($N_{fail} = 4.00$), and lower DT efficiency ($Red_{fail} = 0.80$). It follows that in the complex, this reduces the level of system readiness. It will also lead to longer downtime. In such conditions, despite the lower initial cost of labor and components, the system will require larger volumes of spare parts. In addition, it is also necessary to pay attention to significant energy costs ($E_0 = 8000$ kWh/year). These aspects will also cause environmental impact. And from an economic point of view, this increases the total operating costs, and, accordingly, extends the payback period of the project.

The baseline scenario demonstrates moderate improvements in key parameters. A decrease in the failure rate ($P_f = 0.08$), a decrease in repair time, energy savings, and almost half the need for spare parts – these and other factors indicate that the elements of the circular economy are finally beginning to be implemented in the baseline scenario. For example, it is about the reuse and recovery of components, the modernization of components, a decrease in waste generation, etc. In fact, this contributes to a decrease in the cost of parts (C_{parts}) and direct environmental costs (C_{envDT}) – while simultaneously reducing the carbon footprint. It should also be noted that an increase in the availability factor ($U_{DT} = 0.96$) with an increase in the equipment working time fund provides stable income by increasing the margin.

Table 2

Input data for the economic assessment of the feasibility of implementing the technology of a digital twin of the aircraft hydraulic system, which implements

Indicators, symbols	Scenarios			Units
	Pessimistic	Baseline	Optimistic	
Basic probability of component failure per cycle, P_f	0.10	0.08	0.06	frequent per cycle
Failure rate (without DT), N_{fail}	4.00	3.50	3.00	fault rate per 1000 hours
Failure reduction factor due to DT, Red_{fail}	0.80	0.89	0.98	fraction [0 ... 1]
Accuracy of AI reports, Q_{report}	0.92	0.94	0.95	frequent [0 ... 1]
Repair preparation time, T_{setup}	11	10	9	hours
Repair time (without DT), $T_{repair0}$	40	38	36	hours
Repair time (with DT), $T_{repairDT}$	20	17	15	hours
Labor cost (MO), C_{labor}	88	90	92	USD/hour
Average cost of parts per incident, C_{parts}	12000	11500	10500	USD/Incident
Spare parts reserves (without DT), S_{spare0}	120000	130000	140000	USD
Spare parts reserves (with DT), $S_{spareDT}$	64247	50354	57208	USD
Availability factor (without DT), U_0	0.92	0.92	0.93	frequent [0 ... 1]
Availability factor (with DT), U_{DT}	0.95	0.96	0.96	frequent [0 ... 1]
Equipment working time fund, H_{op}	2900	3000	3200	hours/year
Margin (income per hour), *Margin*	1400	1900	2400	USD/hour
Energy consumption (without DT, year), E_0	8000	7800	7200	kWh/year
Energy consumption (with DT, annual), E_{DT}	6200	5600	5200	kWh/year
Electricity tariff energy, *Tariff*	0.14	0.14	0.14	USD/kWh
Specific grid emissions, EF_{grid}	0.35	0.35	0.35	kg CO_2e/kWh
CO_2 price, CO_{2price}	80	80	80	USD per t CO_2e
Carbon footprint of production of a set of parts, EF_{part}	120	100	90	kg CO_2e/incident
Direct eco-costs (without DT), C_{env0}	4000	3000	2500	USD/year
Direct eco-costs (with DT), C_{envDT}	2200	1500	1200	USD/year
Initial investment, *CAPEX*	1542.815	1695.668	1315.070	thousand USD
IT and cybersecurity support (annual), *OPEXIT*	55000	45000	40000	USD/year
Training (one-time), I_{train}	30000	30000	30000	USD
Discount rate, *DiscRate*	0.15	0.12	0.10	frequent [0 ... 1]
Horizon (years), *Horizon*	7	7	7	years

It should be understood that the optimistic scenario models the conditions for maximum disclosure of the DT potential. Here, the lowest probability of failures is observed ($P_f = 0.06$). Also, here, the highest incident reduction coefficient due to DT ($Red_{fail} = 0.98$). And what is important, this makes it possible to almost completely avoid unplanned downtime. Note that the high accuracy of AI reports, halving the repair time, increasing the working time fund ($H_{op} =$ $= 3200$ hours/year) and the highest margin (2400 USD/hour) create conditions for a sharp increase in profitability. It is in this scenario that the principles of circularity (recovery, reuse of components) are most fully implemented. To the above, it is possible to add the fact of reducing the carbon footprint of production (EF_{part}) and minimizing direct eco-costs (C_{envDT}). They cause a significant reduction in both material and energy resources.

In general, the transition from the pessimistic to the baseline and optimistic scenarios is characterized by a consistent increase in reliability, availability, productivity and marginal revenue while simultaneously reducing costs. However, this does not exhaust all aspects of the study. After all, increasing the implementation of circular approaches in the baseline, and especially in the optimistic scenarios, provides additional environmental and economic efficiency. This, accordingly, increases the overall attractiveness of the DT technology in a favorable implementation environment.

3.3. Modeling of development scenarios, cash flows and efficiency of technology implementation based on circularity

To assess the feasibility of implementing the DT technology of the aircraft hydraulic system, scenario modeling of key indicators of its efficiency was conducted. This approach allows comparing the expected results of the system operation under different levels of technical risks, intensity of operation and volume of investment costs. It should be emphasized that the above makes it possible to determine the potential economic return from the DT use.

The calculations were carried out under three scenarios – pessimistic, baseline and optimistic. This helps to identify the range of possible values of technical, economic and environmental indicators and assess the stability of the technology to changes in external and internal factors. It is important that the scenario approach also creates conditions for assessing the contribution of the principles of the circular economy. For example, from their partial implementation in the baseline scenario, to full-scale implementation in the optimistic scenario – in reducing costs, resource consumption, optimizing the carbon footprint, etc. Accordingly, this justifies under what conditions the technology will provide the highest long-term efficiency.

The results of the scenario assessment of the efficiency indicators of the aircraft hydraulic system digital twin according to the pessimistic, baseline and optimistic development scenarios are given in Table 3.

Table 3

Scenario results of the assessment of the efficiency indicators of the aircraft hydraulic system digital twin

Indicators, units	Notes	Scenarios		
		Pessimistic	Baseline	Optimistic
CO_2 emissions from energy, t/year (excluding DT)	$E_0 * EF_{grid} / 1000$ $(t\ CO_2e / year)$	2.8	2.73	2.52
CO_2 emissions from energy, t/year (including DT)	$E_{DT} * EF_{grid} / 1000$ $(m\ CO_2e / year)$	2.17	1.96	1.82
CO_2 cost of energy, USD/year, (excluding DT)	Ground tests	224	218.4	201.6
CO_2 cost of energy, USD/year, (including DT)	Ground tests	173.6	156.8	145.6
Cost of incident, USD/year, (excluding DT)	$C_{parts} + C_{labor} * (T_{setup} + T_{repair0}) + Margin * (T_{setup} + + T_{repair0}) + C_{env0} + CO_2$	92112	110244	125364
Cost of incident, USD/year, (including DT)	$C_{parts} + C_{labor} * (T_{setup} + T_{repairDT}) + Margin * (T_{setup} + + T_{repairDT}) + C_{envDT} + CO_2$	60501.6	66903.6	71681.6
Annual losses, USD/year, (excluding DT)	Values are obtained by aggregating all incident and downtime costs during the year, excluding the DT impact	368448	322392	276336
Number of incidents per year, failure rate per 1000 hours	$N_{fail} = Annual\_losses / Cost\_per\_incident$ $(without\ DT)$	4.0	3.5	3.0
Annual electricity cost savings, USD/year, (including DT)	$(E_0 - E_{DT}) * Tariff$	63889.6896	34600.86504	12523.831
CO_2 emission reduction, t CO_2e/year	$CO_2(without) - CO_2(with)$	0.252	0.308	0.280
CO_2 cost savings (per incident) *, USD/incident	$CO_{2parts} = (CO_{2price} \times EF_{part}) / 1000$	50.4	61.6	56
CO_2 cost savings in detail (annual) *, USD/year	$(N_{fail} - N_{fail\_dt}) * CO_{2parts}$	9.6	8	7.2
Additional revenue due to increased readiness (year), USD/year	$(U_{DT} - U_0) \times H_{op} \times Margin$	741888	737881.2	703836
Other effects (Loss↓ + Energy + + CO_2), USD/year	$(Loss_0 - Loss_{DT}) + Energy\_saving + CO_2\_saving$	121800	228000	230400
Total revenue effect, USD/year	$Gain_U + (Loss_0 - Loss_{DT}) + Energy\_saving + CO_2\_saving$	863688	965881.2	934236
Annual support costs, USD/year (*OPEX*)	$OPEX = CIT + I_{train} + C_{cyber} + \ldots$ *(all operating costs to support the operation of the digital twin)*	55000	45000	40000
Net cash flow, USD/year	$NCF = Annual\_saving - OPEX$	808688	920881.2	894236

Notes: * – calculation based on CO_2 price ≈80–100 USD/t and specific emissions ≈0.5–0.8 t CO_2/incident (operational fuel costs). Boundaries – energy emissions only (Scope 1/2), excluding spare parts production or logistics

When analyzing the calculated technical and economic indicators, clear differences are visible between the pessimistic, baseline and optimistic scenarios for the implementation of the DT technology in the aircraft hydraulic system. According to the pessimistic scenario, the highest CO_2 emissions from energy consumption are observed (2.8 t/year without DT and 2.17 t/year with DT), the lowest electricity savings (63.9 thousand USD/year) and the low effect of reducing emissions (0.252 t CO_2e/year). The cost of one incident without DT is 92.1 thousand USD, and with its use – 60.5 thousand USD. Yes, this gives significant, but not yet maximum savings. Annual losses without DT still remain high (368.4 thousand USD), and the number of incidents is the largest (4 per year). At the same time, although the additional revenue due to increased readiness reaches 741.9 thousand USD/year, the total revenue effect is the lowest among the scenarios (863.7 thousand USD/year). The net cash flow is 808.7 thousand USD/year for relatively high support costs (*OPEX* = 55 thousand USD/year). In this scenario, the principles of circularity are practically not implemented: no significant reduction in resource consumption or reuse of components is envisaged, which, accordingly, limits environmental and economic efficiency. That is, the system works, but does not do so on the basis of sustainable development. The baseline scenario demonstrates an improvement in almost all key parameters. CO_2 emissions are reduced to 2.73 t/year without DT and 1.96 t/year with DT. In addition, annual electricity savings are 34.6 thousand USD/year. The cost of one incident without DT increases to 110.2 thousand USD (due to higher margin and labor costs). However, with DT it decreases significantly – to 66.9 thousand USD, which with a smaller number of incidents (3.5 per year) gives a significant reduction in annual losses to 322.4 thousand USD/year. It is worth adding to the above argument that the highest effect of "other" components of savings is observed here – reduction of losses, energy consumption and CO_2 (228 thousand USD/year).

It is possible to note that in this scenario, elements of the circular economy are implemented – in particular, partial recovery of components, reuse of parts and reduction of material consumption of repairs, which reduces direct environmental costs (C_{envDT}) and carbon footprint (EF_{part}). Due to this, the total revenue effect reaches 965.9 thousand USD/year, and net cash flow increases to 920.9 thousand USD/year with a decrease in annual support costs (to 45 thousand USD/year).

As the results show, the most significant effect can be achieved under the optimistic scenario. For example, from the reduction in the number of incidents (three per year), downtime and costs per incident (125.4 thousand USD without DT vs. 71.7 thousand USD with DT).

At the same time, CO_2 emissions are also the lowest here – 2.52 t/year without DT and 1.82 t/year with DT, and the annual electricity savings are 12.5 thousand USD/year. Although the annual losses without DT are the lowest here (276.3 thousand USD), the "other" effects from the reduction in losses, energy and CO_2 are the highest (230.4 thousand USD/year). The study of the data indicates another important detail – the additional income due to preparedness remains high (703.8 thousand USD/year). The total income effect is 934.2 thousand USD/year at the lowest operating costs (40 thousand USD/year). In this scenario, the principles of circularity are most fully implemented – large-scale recovery and reuse of components are provided. Also, a reduction in the production volumes of new parts and, accordingly, a reduction in their carbon footprint (EF_{part}). This provides a significant reduction in eco-costs (C_{envDT}).

For a comprehensive assessment of the economic feasibility of implementing the DT technology of the hydraulic predictive maintenance system and establishing the impact of circularity factors, it is possible to analyze the projected cash flows under pessimistic, baseline and optimistic scenarios (Table 4). This will allow to quantitatively assess the time dynamics of the return on investment. Also, this will help establish the break-even point, and will make it possible to compare the total economic effect taking into account the time value of money factor (discounted values).

So, it is here that it becomes clear whether the analyzed DT technology has the potential for real implementation, and is not limited to the level of a conceptual model. Analysis of cash flows in different scenarios shows how the gradual implementation of the principles of the circular economy, from partial to full-scale, affects the cost structure. How exactly they determine the increase in the profitability of DT technology in the long term.

If to compare the cash flows in three possible scenarios – pessimistic, baseline and optimistic – it becomes noticeable that the rate of return on investment and the scale of economic benefits from the DT are formed in completely different ways. First of all, it depends on how the technological implementation will unfold. According to the pessimistic scenario, the initial investment is 1.59 million USD, and the annual net flow is 808.7 thousand USD. The cumulative flow enters the positive zone only at the border of 2–3 years (25 thousand USD in the 2nd year), and the discounted cumulative flow at a rate of 10% remains negative until the end of the 3rd year (–188.8 thousand USD) and becomes positive only from the 4th year (971.1 thousand USD in the 4th year). The final discounted benefit (*NPV*) over 7 years is 2.34 million USD. This indicates a slow return on investment and high risk: the technology provides savings by reducing incidents and downtime. It is worrying that the principles of circularity are practically not implemented (since there is no recovery and reuse of components). The carbon footprint remains high, and therefore indirect environmental costs remain. Together, all of the above limits the potential for long-term efficiency. The baseline scenario assumes higher initial investments – 1.73 million USD but also a significantly higher annual net flow – 920.9 thousand USD. What is promising is that thanks to this, the cumulative flow enters the positive zone already in the 2nd year (116.1 thousand USD), and the discounted flow – from the beginning of the 3rd year (564.4 thousand USD). After seven years, the baseline scenario generates a discounted cumulative flow of 2.75 million USD. This result is achieved not only by reducing the number of incidents and downtime, but also by implementing basic elements of circularity – partial restoration of nodes, reuse of components, reducing the need for the production of new parts, etc. This reduces material and environmental costs. In addition, it stabilizes the cost, creating the prerequisites for the scalability of the technology. In the optimistic scenario, the initial investment is the lowest – 1.41 million USD. The annual flow is 894.2 thousand USD. At the same time, the break-even point is reached already in the 2nd year (382.9 thousand USD of cumulative flow). The discounted cumulative flow itself becomes positive much earlier than in the baseline – already in 2–3 years (148.3 thousand USD in year 2 and 821.8 thousand USD in year 3). Over seven years, the discounted effect is 2.95 million USD. This is the highest financial result among the scenarios, which can be achieved thanks to a combination of increased readiness, reduced incidents, maximum margin, etc. At the same time, it is in this scenario that the principles of circularity are most fully implemented. It provides for comprehensive restoration and modernization of components, their reuse, reduction of production of new parts and a corresponding reduction in carbon footprint and eco-costs. It should be noted that this additionally increases profitability, as not only direct costs are reduced, but also the need for capital expenditures on materials.

So, in conclusion, it is possible to see a clear trend: when moving from the pessimistic to the baseline and optimistic scenarios, there is a reduction in the payback period, an increase in *NPV*, an increase in the stability of cash flows, etc. At the same time, it is obvious that the gradual increase in the level of circularity – from its absence in the pessimistic scenario to full-scale application in the optimistic one, plays a key role in shaping the long-term effectiveness of the DT technology.

A graphical representation of these results is shown in Fig. 2.

Table 4

Cash flows and their discounted values under pessimistic, baseline and optimistic scenarios of implementing a digital twin of a hydraulic predictive maintenance system, USD

Year	Cash flow (Pessim.)	Cumulative cash flow	Present value of cash flow (Pessim.)	Discounted cumulative cash flow	Cash flow (Baseline)	Cumulative cash flow	Present value of cash flow (Baseline)	Discounted cumulative cash flow	Cash flow (Opt.)	Cumulative cash flow	Present value of cash flow (Opt.)	Discounted cumulative cash flow
0	–1592348.11	–1592348.11	–1592348.11	–1592348.11	–1725668.31	–1725668.31	–1725668.31	–1725668.31	–1405541.23	–1405541.23	–1405541.23	–1405541.23
1	808688	–783660.11	735170.91	–857177.20	920881.2	–804787.11	837164.73	–888503.58	894236	–511305.23	812941.82	–592599.41
2	808688	25027.89	668337.19	–188840.01	920881.2	116094.09	761058.84	–127444.74	894236	382930.77	740856.20	148256.79
3	808688	833715.89	607579.26	418739.25	920881.2	1036975.29	691871.67	564426.93	894236	1277166.77	673505.64	821762.43
4	808688	1642403.89	552344.78	971084.03	920881.2	1957856.49	628065.15	1192492.08	894236	2171402.77	611368.76	1433131.19
5	808688	2451091.89	502131.62	1473215.65	920881.2	2878737.69	570059.23	1762551.31	894236	3065638.77	555789.78	1988920.97
6	808688	3259779.89	456483.29	1929698.94	920881.2	3799618.89	516417.48	2278968.79	894236	3959874.77	504354.35	2493275.32
7	808688	4068467.89	414984.81	2344683.75	920881.2	4720500.09	467652.25	2746621.04	894236	4854110.77	457594.86	2950870.18

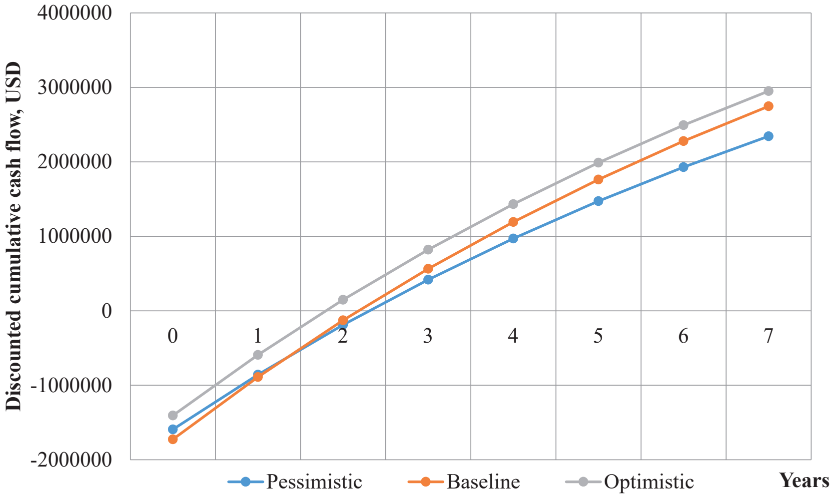

Fig. 2. Dynamics of discounted cumulative cash flows according to the scenarios of implementation of the digital twin of the aircraft hydraulic system

The analysis of cash flows and discounted efficiency clearly demonstrates the different rate of return on investment according to the scenarios. Also, the level of risk and the scale of the economic effect differ. Please note that for a full assessment of the feasibility of implementing the DT technology, it is not enough to consider only the dynamics of cash flows over time. In order to substantiate the investment decision, it is advisable to summarize the results obtained in the form of key integral performance indicators. These are: net present value (*NPV*), internal rate of return (*IRR*), payback period (*PB*), profitability index (*PI*). These indicators make it possible to compare scenarios with each other not only in terms of the speed of achieving breakeven, but also in terms of overall financial attractiveness. They also indicate financial stability taking into account the time factor. Let's add to this the value of the impact of circular practices on costs and revenues (Table 5).

Table 5

Integrated financial and economic performance indicators according to the scenarios for implementing a digital twin of the aircraft hydraulic system

Indicators, units	Scenarios		
	Pessimistic	Baseline	Optimistic
Initial investment (*CAPEX*), USD	1592348	1725668	1405541
Annual net cash flow (*NCF*), USD	808688	920881	894236
Amount of *NCF* for 7 years, USD	5660816	6446168	6259652
Payback period, years	1.96	1.87	1.57
ROI (7 years), %	255	273	345
NPV (10%), USD	2344684	2746621	2950870
IRR, %	42	43	48
Index of return (*PI*)	2.47	2.59	3.10

Comparing the final financial indicators under three scenarios – pessimistic, baseline and optimistic, it becomes obvious that the effectiveness of the implementation of the aircraft hydraulic system DT directly depends on the scale of integration of the principles of the circular economy.

According to the pessimistic scenario, the initial investment (*CAPEX*) is 1592348 USD, and the annual net cash flow (*NCF*) is 808688 USD. Over 7 years, the amount of accumulated flows reaches 5.66 million USD, but the payback period is 1.96 years, and the profitability index (*PI*) is only 2.47. Thus, the technology project remains economically feasible (*NPV* = 2344684 USD; *IRR* = 42%), but it demonstrates the slowest return on investment. The main reason is the practical absence of circular practices. This leads to a high share of costs for new parts, increased environmental impact. As a result, despite the savings on incidents and downtime, a significant part of the funds continues to be spent on primary materials and recycling.

The baseline scenario, on the other hand, demonstrates an improvement in most indicators. It is possible to see that the initial investment increases to 1725668 USD, but the annual *NCF* is already 920881 USD. The sum of flows for 7 years is 6.45 million USD. The payback period is reduced to 1.87 years, the *ROI* reaches 273%, and the *NPV* is 2746621 USD with an *IRR* of 43% and a *PI* of 2.59. It should be noted that this result is explained not only by a decrease in the frequency of incidents and downtime, but also by the beginning of the implementation of circularity principles. These include: partial restoration of components, reuse of components, reduction in the production of new parts, etc. This makes it possible to reduce material and environmental costs. At the same time, this will stabilize the cost (while ensuring a more predictable level of profitability).

The optimistic scenario demonstrates the best integrated results. The initial investment here is the lowest – 1405541 USD. At the same time, the annual *NCF* is 894236 USD, and the total flows for 7 years are 6.26 million USD. The payback period is reduced to 1.57 years, the *ROI* increases to 345%, and the *NPV* – to 2950870 USD. The internal rate of return reaches 48%, and the profitability index is 3.10. Taken together, this all demonstrates the highest investment efficiency among all scenarios. The decisive role in achieving such results is played by the full-scale implementation of the principles of the circular economy. In particular, it is worth mentioning the comprehensive recovery and modernization of components, their reuse, reduction of the production of new parts, reduction of the carbon footprint. This reduces not only direct costs, but also the need for capital expenditures on materials, ensuring a stable growth of the financial effect throughout the entire life cycle of the technology.

Thus, with an increase in the level of integration of circular approaches, there is a decrease in initial investments, acceleration of the return on investment, growth of *NPV*, *IRR* and *PI*. All this confirms that circularity is a key factor in increasing the economic efficiency of the DT technology in the long term.

Our results have shown that the implementation of the principles of the circular economy significantly enhances the economic efficiency of the DT technology. Accordingly, this reduces the need for initial investments, accelerating the return on investment and ensuring an increase in *NPV*, *IRR* and *PI*. However, one should not forget the fact that the calculations given are based on assumptions regarding constant values of key input parameters. In real conditions, they can change under the influence of various factors (technical, market, organizational, etc.).

3.4. Sensitivity assessment of technology implementation efficiency indicators taking into account circular practices

To analyze the stability of the above results and determine the parameters that most affect the efficiency of technology implementation, it is advisable to conduct a sensitivity assessment. This will allow to determine how much a change in individual output indicators (*CAPEX*, *NCF*, discount rate, level of implementation of circular practices, etc.) affects the integrated financial results (for each of the scenarios considered).

Table 6 presents the results of our sensitivity analysis, which reflect the change in key integrated technology efficiency indicators (*NPV* and *IRR*) with variations in the main input parameters within the baseline scenario, and taking into account the level of implementation of circular practices.

Table 6

Results of sensitivity assessment of integrated financial indicators of the efficiency of the implementation of the aircraft hydraulic system digital twin

Variables	Modeling change	Indicators, units of measurement				
		NCF, USD	*CAPEX*, USD	*r*, %	*NPV*, USD	*IRR*, %
Initial values of variables	–	920881	1725668	10%	2746621	43%
NCF	−20%	736705	1725668	10%	1346016	25%
	−10%	828793	1725668	10%	2046319	34%
	+10%	1012969	1725668	10%	3446923	50%
	+20%	1105057	1725668	10%	4147226	56%
CAPEX	−20%	920881	1380535	10%	3091755	54%
	−10%	920881	1553101	10%	2918188	48%
	+10%	920881	1898235	10%	2575054	39%
	+20%	920881	2070802	10%	2401487	35%
Discount rate	8%	920881	1725668	8%	3226850	43%
	12%	920881	1725668	12%	2374331	43%
	15%	920881	1725668	15%	1905471	43%
Horizon, years	5	920881	1725668	10%	1680174	43%
	7	920881	1725668	10%	2746621	43%
	10	920881	1725668	10%	3797726	43%

Sensitivity analysis allowed to assess how much the change in key input parameters affects the integral financial results of the implementation of this technology. First of all, it is about the net present value (*NPV*) and the internal rate of return (*IRR*).

In particular, under the baseline scenario of the implementation of the aircraft hydraulic system DT technology, with the values of *NCF* = 920881 USD, *CAPEX* = 1725668 USD, a discount rate of 10% and a horizon of 7 years, the project demonstrates *NPV* = 2746621 USD and *IRR* = 43%. This indicates its high efficiency.

The most sensitive factor was the annual net cash flow (*NCF*). Its decrease by 20% leads to a decrease in NPV almost twice – to 1,346,016 USD. But at the same time, the *IRR* also drops from 43% to 25%. Conversely, a 20% increase in NCF increases the *NPV* to 4147226 USD and the *IRR* to 56%. This highlights that the long-term efficiency of the technology critically depends on the stability of revenue generation. The level of implementation of circular practices directly affects this indicator: reducing the cost of new parts (as well as recycling, environmental payments, etc.) increases the margin, and therefore the *NCF* value. Here, it is undeniable that increasing circularity directly increases the sensitivity of *IRR* and *NPV* to the growth of net flows. The second most influential factor is *CAPEX*. Reducing the initial investment by 20% increases the *NPV* to 3091755 USD and the *IRR* to 54%. Increasing it by 20% reduces the *NPV* to 2401487 USD and the *IRR* to 35%. This shows that the efficiency of the investment project significantly depends on the start-up costs. Therefore, circularity works as a stabilizer: it reduces capital costs due to the reuse of components. Accordingly, this also increases the financial sustainability of this DT technology.

At the same time, changing the discount rate within 8–15% has almost no effect on the *IRR* (it remains at 43%), but significantly changes the *NPV*. That is, at 8% it increases to 3226850 USD, at 15% it decreases to 1905471 USD. This is logical, because the higher the discount rate, the lower the present value of future revenues. In this case, circularity manifests itself as an indirect factor in stabilizing the system. Reducing risks due to reduced dependence on purchases, waste, etc. will increase the level of investment attractiveness, will make it possible to apply lower discount rates.

The planning horizon also affects only the *NPV*: when reduced to 5 years, it decreases to 1680174 USD, and when increased to ten years, it increases to 3797726 USD. This is quite expected, since longer use of CDs allows for a more complete realization of the cumulative effect of circular practices (this involves a gradual reduction in the cost of purchasing new parts, a more stable cash flow over time, etc.).

The most critical factors for economic efficiency are the *NCF* value and the size of the initial investment: they depend to the greatest extent on the scale of implementation of the principles of the circular economy. Active recovery and reuse of components leads to a higher level of net flows and lower initial costs. Circularity improves the environmental performance of the project, reducing its financial vulnerability. It provides a more stable payback even with adverse fluctuations in other parameters.

For an in-depth analysis of the economic efficiency of implementing the DT technology of the aircraft hydraulic system, it is advisable to study the sensitivity of the results to the key parameters of the model. Within the framework of such an analysis, a derivative-based approach is used, which allows to quantitatively determine how changes in individual input parameters affect the values of financial indicators. This will provide an opportunity to assess both the obtained economic effect and the speed of its formation. The use of derivatives in the economic evaluation model makes it possible to determine the marginal impact of each parameter on performance indicators, creating a basis for a phased analysis of cash flow dynamics and *NPV* sensitivity to changes in NCF_t, *CAPEX* and discount rate. At the initial stage of model formation, its basic parameters are determined. In particular, the initial investment (*CAPEX*), discount rate (r), planning horizon (T), forecast values of net cash flows (NCF_t) for each year of operation are taken into account. The integral economic efficiency of the project is assessed using the net present value (*NPV*) indicator, which is calculated by the expression

$$NPV = -CAPEX + \sum_{t=1}^{T} \frac{NCF_t}{(1+r)^t}. \qquad (1)$$

To analyze the dynamics of the increase in economic effect, the model uses the concept of the derivative of cumulative cash flow $\frac{dCF(t)}{dt} = NCF(t).$ This approach allows to interpret *NCFt* as the "speed" of growth of the accumulated result. In addition, it is possible to determine in which periods the project will create the largest share of the effect.

The third stage consists in determining analytical derivatives of *NPV* by key parameters. The derivative for NCF_t $\left(\frac{\partial NPV}{\partial NCFt} = \frac{1}{(1+r)^t}\right)$ reflects the discounted value of the cash flow in each year, for *CAPEX* $\left(\frac{\partial NPV}{\partial CAPEX} = -1\right)$ – the direct investment impact, and for r $\left(\frac{\partial NPV}{\partial r} = -\sum_{t=1}^{T} \frac{t \cdot NCF_t}{(1+r)^{t+1}}\right)$ – the sensitivity of the result to changes in the discount rate. For comparisons, the relative elasticities were also used: $E_{NPV,NCF_t} = \frac{DF_t \cdot NCF_t}{NPV}$ and $E_{NPV,CAPEX} = \frac{CAPEX}{NPV}$.

To quantitatively assess the impact of key parameters on the project's performance, marginal increments and NPV elasticities for NCF_t and *CAPEX* were calculated. Accordingly, this was implemented within the baseline scenario (Table 7).

Table 7

Marginal impact and elasticity of net present value (*NPV*) by key parameters in the baseline scenario

Year, *t*	DF_t	ΔNPV + 10000 USD in year *t*	$E_{NPV,NCF_t} = \dfrac{DF_t \cdot NCF_t}{NPV}$
1	0.9091	+9090.91	0.3036
2	0.8264	+8264.46	0.2760
3	0.7513	+7513.15	0.2509
4	0.6830	+6830.13	0.2281
5	0.6209	+6209.21	0.2074
6	0.5645	+5644.74	0.1885
7	0.5132	+5131.58	0.1714

Analysis of the derivatives in Table 7 shows that the largest contribution to the increase in the net present value of the DT project is made by early cash flows. Thus, in the baseline scenario (according to Table 6, *CAPEX* = 1725668 USD, r = 10%, NCF_t = 920881 USD/year, T = 7 years), the discount factors decrease from 0.909 in the 1st year to 0.513 in the 7th. This means: an additional 10000 USD in the 1st year increases the *NPV* by approximately 9091 USD, and in the 7th year – by only 5132 USD. The interpretation of this is to accelerate the formation of flows (due to reduced downtime, in particular). This will significantly increase the economic return on the implementation of DT technology.

The derivative of *CAPEX* has a constant gradient of – 1 (each additional dollar of initial costs directly reduces *NPV* by 1 USD). The relative elasticity *ENPV,CAPEX* ≈ –0.63 indicates that a 10% increase in initial investment reduces *NPV* by approximately 6.3%, meaning that controlling initial costs is of crucial importance in capital-intensive technology projects. The elasticity of *ENPV,NCFt* in year 1 is around 0.30. It gradually decreases to 0.17 in year 7, which in fact confirms the higher importance of early revenues. The total elasticity of NCF_t (≈+1.63) significantly exceeds the modulus of elasticity of *CAPEX* (≈–0.63). This indicates that an increase in operational efficiency has a stronger effect than an equivalent reduction in investment.

In the context of a circular economy, these results are of fundamental importance. Circular practices simultaneously reduce *CAPEX* and increase *NCFt*. That is, they work through both key channels at once, and, therefore, the integration of circularity significantly accelerates the growth of NPV, bringing the project's payback point closer.

3.5. Justification of the controversial provisions and key limitations of the study of the economic assessment of technology

The presented study is characterized by a number of limitations. Among them, one of the most important is that the model is based on fixed values of indicators, which in real conditions can fluctuate significantly under the influence of changes, and this will affect the accuracy of financial forecasting.

The potential effects of increasing flight safety are not taken into account in the financial calculations, which somewhat limits the complexity of the assessment.

The data obtained demonstrate a high sensitivity of the results to the depth of implementation of circular practices. Thus, a 20% reduction in the *NCF* level reduces the *NPV* from 2.75 to 1.35 million USD (*IRR* – from 43% to 25%), and an increase of 20% – increases *NPV* to 4.15 million USD and *IRR* to 56%. This means that any failures in the implementation of these practices can significantly worsen the financial sustainability of the project.

Additionally, the analysis of *NPV* derivatives showed that early cash flows (NCF_t) have twice the marginal impact on the result than late ones. While *CAPEX* operates with a constant negative gradient of –1. This indicates that increasing the level of circularity by reducing start-up costs and accelerating revenue generation is a determining factor in the growth of *NPV*. Accordingly, this will also contribute to reducing the payback period.

3.6. Discussion of the results of the circular economic assessment of the innovative technology

Taking into account the identified limitations, the results of the scenario analysis demonstrated a significant potential for increasing economic and technical efficiency through the implementation of the DT technology of the aircraft hydraulic system for predictive maintenance. All three scenarios considered demonstrated positive financial results. In particular, the net present value (*NPV*) is in the range from 2.34 to 2.95 million USD. The internal rate of return (*IRR*) is from 42% to 48%, and the profitability index (*PI*) is from 2.47 to 3.10. Under the pessimistic scenario (*CAPEX* = 1.59 million USD, *NCF* = 808.7 thousand USD/year), the payback period is 1.96 years, while under the baseline scenario (*CAPEX* = 1.73 million USD, *NCF* = 920.9 thousand USD/year) it is reduced to 1.87 years, and under the optimistic scenario (*CAPEX* = 1.41 million USD, *NCF* = 894.2 thousand USD/year) it is reduced to 1.57 years. Unlike existing studies, in which DTs are considered mainly as a tool for reducing operational risks or increasing technical reliability [3, 4], in this research their role is considered from the perspective of taking into account the principles of circularity. These data also confirm that the main source of the economic effect is not so much the growth of revenues, but the reduction of losses from downtime, emergency repairs, inefficient use of resources for capital-intensive engineering innovations, etc. [4, 11].

The key distinguishing feature of the obtained results is the identified cause-and-effect relationship between the level of integration of circular practices and the dynamics of investment indicators. The transition from a pessimistic to an optimistic scenario is accompanied by a decrease in the need for primary materials, which directly affects the structure of *CAPEX* and *OPEX*. Such an effect corresponds to modern approaches to interpreting the circular economy as an economic, and not only an environmental phenomenon [21, 28]. Unlike existing works, in which circularity is often considered as an external regulatory or ESG factor [21, 30]; in this research it is integrated directly into the model of NPV and IRR formation through changes in key financial parameters.

The analysis of implemented discounted flows showed that in the pessimistic scenario, the cumulative flow becomes positive only at the border of the 2nd–3rd year, in the baseline scenario – at the beginning of the 3rd year, while in the optimistic scenario – already during the 2nd year. The obtained scenario calculations confirm that such dynamics correlate with the level of integration of circular approaches: the higher it is, the earlier the technology reaches stable revenue generation. In parallel, the sensitivity analysis conducted in the work demonstrated a high dependence of the results on key parameters (primarily, *NCF* and *CAPEX*), which are most determined by the scale of the implementation of circular practices. Note that a decrease in *NCF* by 20% reduces the *NPV* from 2.75 to 1.35 million USD and the *IRR* from 43% to 25%, while its increase by 20% increases the *NPV* to 4.15 million USD and *IRR* to 56%. An increase in *CAPEX* by 20% reduces *NPV* to 2.40 million USD and *IRR* to 35%. The results of the sensitivity analysis deepen the interpretation of the mechanisms of efficiency formation. Unlike common approaches, in which the key factor of investment attractiveness of high-tech projects is mostly considered to be initial capital expenditures, the obtained results show the dominant role of net operating cash flows in the formation of integral indicators of *NPV* and *IRR*.

The high sensitivity of these indicators to variations in *NCF* is explained by the fact that it accumulates the simultaneous impact of technical solutions (reduction of failure frequency and duration of repairs) and circular practices (reduction of material, energy and environmental costs). At the same time, unlike works where operational effects are considered in isolation, this research shows that it is their combination within the framework of a circularly oriented model that ensures an outpacing growth of *NPV*. The constant negative impact of *CAPEX*, recorded in the calculations, reflects the capital-intensive nature of the digital twin and does not eliminate, but only emphasizes the crucial role of early operational flows in achieving economic efficiency, which partly contradicts traditional investment models focused mainly on minimizing start-up costs [25, 31].

Additional evaluation based on derivatives confirmed the above trend: early cash flows (NCF_t) have almost twice the marginal impact on *NPV* than late ones. While *CAPEX* operates with a constant negative gradient of –1. This means that it is the DT technology (due to the reduction of failure rates and acceleration of repairs) that is a critical tool for achieving high operational efficiency already at the initial stages. Circular practices (repairability, component reuse, inventory reduction, reduction in the cost of new parts) operate through both key channels – reducing *CAPEX* and increasing *NCF*. Therefore, this ensures an increase in *NPV* and a reduction in the payback period.

In addition, it is important to consider the time aspect: increasing the planning horizon from 5 to 10 years increases the *NPV* from 1.68 to 3.80 million USD. This fact demonstrates the powerful cumulative effect of circularity. At the same time, this requires maintaining the technological relevance of the DT throughout the entire life cycle. Potential risks include equipment obsolescence, degradation of its characteristics, the need to update software and cyber security, as well as organizational barriers in data management. These and other aspects can affect the stability of income and the actual payback period. Therefore, in further research, it is advisable to take into account the effect of decreasing efficiency over time. Characteristic conclusions regarding the long-term return from circularly oriented innovations can be found in works devoted to the assessment of the life cycle of technologies and resource efficiency [11–14]. At the same time, this emphasizes the need to maintain the technological relevance of the DT throughout the entire life cycle. In particular, by updating software, ensuring cyber security, effective data management, etc.

The practical value of research is in the methodological support of the economic assessment of innovative technologies taking into account the principles of the circular economy. The author's approach contributes to the quantitative determination of the impact of the level of circularity on technical and economic performance indicators (*CAPEX*, *NCF*, *NPV*, *IRR*, *PI*). It also makes it possible to identify the marginal effects of key parameters using derivative analysis. This creates practical opportunities for enterprises in high-tech industries (aviation, machine building, energy, etc.) in planning investment programs for technical systems.

The main limitations of research include the use of fixed values of the discount rate and carbon price, as well as assumptions about the stability of operational parameters over time. Similar limitations are inherent in most economic models of evaluating innovative technologies and are recognized in modern studies as a methodological simplification [16, 21, 31]. In addition, the model does not take into account possible systemic risks associated with the DT integration into complex production ecosystems, which may affect the reproducibility of results in other industry or regional conditions.

Further research is aimed at deepening and unifying models for evaluating innovative technologies through the creation of integrated systems capable of reflecting the interrelationship of technical, economic, environmental and social indicators of circularity at all stages of the life cycle.

4. Conclusions

1. To implement the research tasks, an innovative technology was selected – the aircraft hydraulic system DT for predictive maintenance. Its implementation reduces the number of failures, incident costs, energy consumption and CO_2 emissions, increasing technical readiness and profitability of operation. The tasks of the system that actualize its use are: real-time monitoring of parameters; modeling of work; forecasting of failures; automated generation of analytical reports using AI, etc. From the standpoint of sustainable development, the technology extends the life cycle of components. It also reduces waste. Thanks to this, it is possible to ensure the formation of a resource-efficient maintenance system based on the principles of a circular economy.

2. A set of indicators is proposed that reflects both the cost and effective aspects of implementing DT of the aircraft hydraulic system, taking into account the principles of circularity. The system covers five groups of parameters: reliability and risks, resource, operational, sustainable development and management costs. Its application makes it possible to quantitatively assess the impact of the technology on reducing failures. It also contributes to: reducing downtime, extending the life cycle of components, reducing resource consumption, reducing emissions, etc. The scientific originality of the system lies in the fact that circularity is taken into account here not as a declarative ESG context, but as a measurable factor that changes *CAPEX*/*OPEX* and cash flows (*NCF*), i. e. directly affects *NPV*/*IRR*.

Scenario data for the development of the aircraft hydraulic system DT technology were generated taking into account the principles of circularity. Three scenarios were developed – pessimistic, baseline and optimistic. They reflect different levels of integration of circular practices into maintenance processes. The analysis showed: with an increase in the level of circularity, repair costs and downtime are reduced, energy consumption and CO_2 emissions are reduced. At the same time, the system availability factor increases to 0.96. The baseline scenario implements the initial elements of component reuse. Optimistic provides full disclosure of the potential of the technology (extension of the life cycle, reduction of eco-costs, increase in profitability, etc.). The indicator system and scenario database provide a reproducible approach for comparing alternatives (with/without DT). They can be used to justify investment decisions in high-tech industries.

3. The technical, economic, environmental and financial results were calculated for three scenarios and a number of key indicators (*NPV*, *IRR*, *PI*, etc.). A comparison of the technical and economic indicators revealed a fairly clear picture: under the pessimistic scenario, there are the highest CO_2 emissions (2.8 t/year without DT and 2.17 t/year with its use). Electricity savings, respectively, are the smallest (≈63.9 thousand USD/year), and net cash flow is the lowest (≈808.7 thousand USD/year) with fairly high *OPEX* (55 thousand USD/year). The baseline scenario looks noticeably better: emissions are reduced to 2.73 and 1.96 t/year. The cost of the incident is from 110.2 to 66.9 thousand USD, and annual losses are up to ≈322 thousand USD. The net flow, on the other hand, increases to 920.9 thousand USD/year for *OPEX* = 45 thousand USD/year. The optimistic option demonstrates the maximum effect of circular approaches: the probability of failures drops to 0.06, and the costs per incident – from 125.4 to 71.7 thousand USD. CO_2 emissions are reduced to 1.82 t/year. The net cash flow is 894.2 thousand USD/year, and this is at the lowest *OPEX* (about 40 thousand USD/year). If to look at the picture as a whole, the transition from the pessimistic to the optimistic scenario gives more than 10% increase in profitability. This provides a reduction in energy consumption by about 35%, and CO_2 emissions – by almost 30%. Actually, this confirms the importance of circular practices in shaping the technical, economic and environmental performance of the DT.

Analysis of cash flows and financial indicators of the effectiveness of the DT implementation showed the following. Under the pessimistic scenario, *CAPEX* = 1.59 million USD, *NCF* = 808.7 thousand USD/year, *NPV* = 2.34 million USD, *IRR* = 42%, *PI* = 2.47, and the payback period is 1.96 years. Under the baseline scenario: *CAPEX* = 1.73 million USD, *NCF* = 920.9 thousand USD/year, *NPV* = 2.75 million USD, *IRR* = 43%, *PI* = 2.59, payback period is 1.87 years. The optimistic scenario was expected to be the most effective: *CAPEX* = 1.41 million USD, *NCF* = 894.2 thousand USD/year, *NPV* = 2.95 million USD, *IRR* = 48%, *PI* = 3.10. The payback period was reduced to 1.57 years. As a result, the transition from the pessimistic to the optimistic scenario is accompanied by an increase in *NPV* by 26%, *PI* – by 25% and a reduction in the payback period by another 0.4 years. The difference in the obtained quantitative results indicates a cause-and-effect relationship: increased circularity – lower incident/downtime and eco-costs – higher *NCF* and better integrated indicators of investment efficiency.

4. An analysis of the sensitivity of *NPV*/*IRR* to changes in *NCF*, *CAPEX*, discount rate and planning horizon was performed; additionally, a derivative approach was applied to estimate the marginal contribution of the parameters. The result obtained indicates that it is the annual net cash flow and initial investment that "weight" the most. Under baseline conditions, the *NPV* is 2.75 million USD and the *IRR* is 43%. If to reduce the *NCF* by 20%, this reduces the *NPV* to 1.35 million USD and the *IRR* drops to 25%. An increase of 20% gives a different picture – an increase in *NPV* to 4.15 million USD and an *IRR* of 56%.

Regarding *CAPEX*: its reduction by 20% increases *NPV* to 3.09 million USD, and *IRR* to 54%. If *CAPEX*, on the contrary, increases by the same 20%, then *NPV* decreases to 2.40 million USD, and *IRR* to 35%. Variation of the discount rate (within 8–15%) has almost no effect on *IRR*. However, it still changes the *NPV* indicator – from 1.9 to 3.2 million USD. Extending the planning horizon from 5 to 10 years actually "stretches" the effect: *NPV* increases from 1.68 to 3.80 million USD.

The marginal impact of key parameters was estimated using the derivative method. Calculations showed that an additional 10,000 USD received in the first year causes an increase in *NPV*, in particular, to the mark of 9,091 USD, while for later periods (for example, in the seventh year), the similar increase decreases to 5,132 USD. It is observed that early receipts play a key role in shaping the result. The derivative of *CAPEX* has a gradient of −1, and the elasticity $E_{npv,CAPEX} \approx -0.63$, which in practice means a decrease in *NPV* by approximately 6.3%, in the case of an increase in investment by 10%.

5. The initial framework of the research work is justified. The accuracy of the assessment is limited by assumptions about the stability of the parameters and the planning horizon (5–10 years). In a real situation, these assumptions may not be met due to a number of problematic situations. Socio-economic effects – increased safety, reliability and working conditions – remain outside the scope of financial assessment. As well as the full life cycle of environmental impacts. The most significant factor was identified as the level of circularity: a change in *NCF* by ±20% varies the *NPV* from 1.35 to 4.15 million USD, and the *IRR* from 25% to 56%. Derivative analysis confirmed the twice greater importance of early NCF_t flows compared to late ones. This emphasizes that increasing the level of circularity through *CAPEX* reduction and revenue acceleration is a key factor in increasing the *NPV* and financial sustainability of the project. Clear boundaries allow practitioners to transfer the model to their own conditions and plan for further expansion of the model.

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.

Financing

The research was performed without financial support.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

For auxiliary computational operations within the framework of research (section 3 "Results and Discussion"), the OpenAI cloud artificial intelligence tool (version 5.1) was used, which supports the processing of multi-digit numerical data and their export to spreadsheet format. The authors independently verified the correctness of the calculations and performed analytical interpretation of the results. The data were checked by duplicating key calculations in the Excel environment. Additionally, independent manual control of intermediate values (*NPV*, *IRR*, *PI*, discounting, *NPV* derivatives, etc.) was carried out.

The use of the AI tool did not affect the formation of the research conclusions, since its role was limited only to technical support of computational procedures, without interfering with the content aspects.

Authors' contributions

Viktoriia Prokhorova**:** Project administration; ***Oleksandra Mrykhina*****:** Conceptualization, Methodology, Supervision; ***Orest Koleshchuk*****:** Investigation, Data curation, Validation; ***Krystyna Slastianykova*****:** Conceptualization, Formal analysis, Resources; ***Roman Paraniuk*****:** Resources, Writing – review and editing; ***Darii Koleshchuk*****:** Software, Resources, Writing – original draft.

References

1. *Airlines Maintenance Cost Executive Commentary. FY2021 Data* (2022). International Air Transport Association. Available at: https://www.scribd.com/document/773131044/Iata-Fy2021-Mctg-Report-public
2. Karunaratne, T., Ajiero, I. R., Joseph, R., Farr, E., Piroozfar, P. (2025). Evaluating the Economic Impact of Digital Twinning in the AEC Industry: A Systematic Review. *Buildings, 15 (14),* 2583. https://doi.org/10.3390/buildings15142583
3. Malik, A. A. (2024). The Economic Impact of Digital Twin Technology on Manufacturing Systems. *2024 Winter Simulation Conference (WSC).* IEEE, 1623–1633. https://doi.org/10.1109/wsc63780.2024.10838771
4. Thomas, D. (2024). Economics of digital twins: Costs, benefits, and economic decision making *(NIST Advanced Manufacturing Series No. AMS 100-61).* National Institute of Standards and Technology. https://doi.org/10.6028/nist.ams.100-61
5. Mügge, J., Seegrün, A., Hoyer, T.-K., Riedelsheimer, T., Lindow, K. (2024). Digital Twins within the Circular Economy: Literature Review and Concept Presentation. *Sustainability, 16 (7),* 2748. https://doi.org/10.3390/su16072748
6. Cao, M., Song, W., Xu, Y. (2024). Research on the impact of enterprise digital transformation based on digital twin technology on renewable energy investment decisions. *Energy Informatics, 7 (1).* https://doi.org/10.1186/s42162-024-00447-8
7. Kou, G., Dinçer, H., Yüksel, S., Deveci, M. (2024). Synergistic integration of digital twins and sustainable industrial internet of things for new generation energy investments. *Journal of Advanced Research, 66,* 39–46. https://doi.org/10.1016/j.jare.2023.11.023
8. Palea, V., Santhià, C., Miazza, A. (2023). Are circular economy strategies economically successful? Evidence from a longitudinal panel. *Journal of Environmental Management, 337,* 117726. https://doi.org/10.1016/j.jenvman.2023.117726
9. Georgescu, I., Kinnunen, J., Androniceanu, A.-M. (2022). Empirical evidence on circular economy and economic development in Europe: a panel approach. *Journal of Business Economics and Management, 23 (1),* 199–217. https://doi.org/10.3846/jbem.2022.16050
10. Georgescu, L. P., Fortea, C., Antohi, V. M., Balsalobre-Lorente, D., Zlati, M. L., Barbuta-Misu, N. (2025). Economic, technological and environmental drivers of the circular economy in the European Union: a panel data analysis. *Environmental Sciences Europe, 37 (1).* https://doi.org/10.1186/s12302-025-01119-4

11. Prokhorova, V. V., Yemelyanov, O. Y., Koleshchuk, O. Y., Petrushka, K. I. (2023). Tools for assessing obstacles in implementation of energy saving measures by enterprises. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 1,* 160–168. https://doi.org/10.33271/nvngu/2023-1/160

12. Prokhorova, V., Mrykhina, O., Koleshchuk, O., Babichev, A., Dudnieva, I., Slastianykova, K. (2025). Economic assessment of intellectual and innovative technologies in the context of sustainable development. *Technology Audit and Production Reserves, 1 (4 (81)),* 37–50. https://doi.org/10.15587/2706-5448.2025.323977

13. Prokhorova, V., Yemelyanov, O., Koleshchuk, O., Shepelenko, S., Slastianykova, K. (2025). Assessment of the impact of technological changes on the dynamics of enterprises' economic development. *Technology Audit and Production Reserves, 4 (4 (84)),* 13–23. https://doi.org/10.15587/2706-5448.2025.334782

14. Marchioni, A., Magni, C. A. (2018). Investment decisions and sensitivity analysis: NPV-consistency of rates of return. *European Journal of Operational Research, 268 (1),* 361–372. https://doi.org/10.1016/j.ejor.2018.01.007

15. Mokhtari, H., Kiani, S., Tahmasebpoor, S. S. (2018). Economic Evaluation of Investment Projects Under Uncertainty: A Probability Theory Perspective. *Scientia Iranica, 25 (6),* 3391–3404. https://doi.org/10.24200/sci.2018.50256.1599

16. Chai, S. Y. W., Phang, F. J. F., Yeo, L. S., Ngu, L. H., How, B. S. (2022). Future era of techno-economic analysis: Insights from review. *Frontiers in Sustainability, 3.* https://doi.org/10.3389/frsus.2022.924047

17. Zimmermann, A. W., Langhorst, T., Moni, S., Schaidle, J. A., Bensebaa, F., Bardow, A. (2022). Life-Cycle and Techno-Economic Assessment of Early-Stage Carbon Capture and Utilization Technologies – A Discussion of Current Challenges and Best Practices. *Frontiers in Climate, 4.* https://doi.org/10.3389/fclim.2022.841907

18. Sulin, S. N., Mokhtar, M. N., Baharuddin, A. S., Mohammed, M. A. P. (2025). Simulation and techno-economic evaluation of integrated palm oil mill processes for advancing a circular economy. *Cleaner Environmental Systems, 19,* 100323. https://doi.org/10.1016/j.cesys.2025.100323

19. Dennison, M. S., Kumar, M. B., Jebabalan, S. K. (2024). Realization of circular economy principles in manufacturing: obstacles, advancements, and routes to achieve a sustainable industry transformation. *Discover Sustainability, 5 (1).* https://doi.org/10.1007/s43621-024-00689-2

20. Pérez-Almada, D., Galán-Martín, Á., Contreras, M. del M., Castro, E. (2023). Integrated techno-economic and environmental assessment of biorefineries: review and future research directions. *Sustainable Energy & Fuels, 7 (17),* 4031–4050. https://doi.org/10.1039/d3se00405h

21. Chukhray, N., Mrykhina, O., Bespaliuk, K., Chukhrai, A. (2025). A price-determining model for industrial "technology-push" innovations. *Innovative Marketing, 21 (4),* 27–44. https://doi.org/10.21511/im.21(4).2025.03

22. Kowszyk, Y., Maher, R. (2018). Case studies on circular economy models and integration of Sustainable Development Goals in business strategies in the EU and LAC. *EU-LAC Foundation & InnovacionAL SpA.EU-LAC Foundation.* Available at: https://eulacfoundation.org/en/system/files/case_studies_circular_economy_eu_lac.pdf

23. Jones, P., Comfort, D. (2021). The Circular Economy: An Exploratory Case Study from the Paper and Retail Industries. *Athens Journal of Business & Economics, 7 (4),* 379–394. https://doi.org/10.30958/ajbe.7-4-5

24. Chiscop, F., Vlase, A. I., Cazacu, C.-C., Popa, C. L., Cotet, C. E. (2025). Manufacturing Productivity Improvement by Integrating Digital Tools Illustrated in the Optimization of a Hub Assembly Line. *Machines, 13 (9),* 849. https://doi.org/10.3390/machines13090849

25. Mrykhina, O., Didukh, N., Korytska, O., Stepura, T. (2024). Implementation of Digital Tools in Teaching of Interdisciplinary Courses in Higher Educational Institutions. *2024 IEEE 19th International Conference on Computer Science and Information Technologies (CSIT).* IEEE, 1–5. https://doi.org/10.1109/csit65290.2024.10982611

26. Bauwens, T. (2021). Are the circular economy and economic growth compatible? A case for post-growth circularity. *Resources, Conservation and Recycling, 175,* 105852. https://doi.org/10.1016/j.resconrec.2021.105852

27. Corona, B., Shen, L., Reike, D., Rosales Carreón, J., Worrell, E. (2019). Towards sustainable development through the circular economy – A review and critical assessment on current circularity metrics. *Resources, Conservation and Recycling, 151,* 104498. https://doi.org/10.1016/j.resconrec.2019.104498

28. da Cunha Moraes, T. E., Ferasso, M., Alves Teixeira, A. (2025). Economic complexity and the Circular Economy: Impacts, challenges and paths to circularity. *Journal Managment & Business Studies, 7 (1).* https://doi.org/10.32457/jmabs.v7i1.3041

29. Martínez Moreno, M. M., Buitrago Esquinas, E. M., Yñiguez, R., Puig-Cabrera, M. (2023). A global and comparative assessment of the level of economic circularity in the EU. *Journal of Cleaner Production, 425,* 138759. https://doi.org/10.1016/j.jclepro.2023.138759

30. Negrei, C., Istudor, N. (2018). Circular Economy: Between Theory and Practice. *Amfiteatru Economic Journal, 20 (48),* 498. https://doi.org/10.24818/ea/2018/48/498

31. Shpak, N., Muzychenko-Kozlovska, O., Gvozd, M., Sorochak, O. (2025). Assessment of the Investment and Innovation Environmental Attractiveness of the Country: On the Example of Ukraine. *Systems, Decision and Control in Energy VII.* Cham: Springer, 795–816. https://doi.org/10.1007/978-3-031-90466-0_37

Viktoriia Prokhorova, *Doctor of Economic Sciences, Professor, Head of Department of Economics and Management, V. N. Karazin Kharkiv National University, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0003-2552-2131*

Oleksandra Mrykhina, *Doctor of Economic Sciences, Professor, Department of Business Economics and Investment, Lviv Polytechnic National University, Lviv, Ukraine, ORCID: https://orcid.org/0000-0002-0567-2995*

✉***Orest Koleshchuk,*** *Doctor of Economic Sciences, Associate Professor, Department of Business Economics and Investment, Lviv Polytechnic National University, Lviv, Ukraine, e-mail: orest.y.koleshchuk@lpnu.ua, ORCID: https://orcid.org/0000-0001-8995-5206*

Krystyna Slastianykova, *Assistant, Department of Economics and Business Administration, V. N. Karazin Kharkiv National University, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-7114-5165*

Roman Paraniuk, *PhD Student, Department of Economics and Business Administration, V. N. Karazin Kharkiv National University, Kharkiv, Ukraine, ORCID: https://orcid.org/0009-0000-8854-5328*

Darii Koleshchuk, *Department of Foreign Trade and Customs, Lviv Polytechnic National University, Lviv, Ukraine, ORCID: https://orcid.org/0009-0009-7680-2142*

✉*Corresponding author*