14. Коваленко В. Ф., Левченко П. Г., Шутов С. В. Кластерная природа светорассеяния воды. *Биомедицинская радиоэлектроника*. 2008. № 5. С. 36–45.
15. Бункин Н. Ф., Суязов Н. В., Ципенюк Д. Ю. Малоугловое рассеяние лазерного излучения на стабильных образованиях микронного масштаба в дважды дистиллированной воде. *Квантовая электроника*. 2005. Т. 35. № 2. С. 180–184.
16. Коваленко В. Ф., Бордюк А. Ю., Шутов С. В. Определение формы кластеров воды. *Оптика атмосферы и океана*. 2011. Т. 24. № 7. С. 601–605.
17. Нестерюк П. И. Измерительно-вычислительный комплекс и методы исследований физико-химических параметров воды после воздействия физических полей: автореф. дис. … канд. техн. наук: 01.04.01 / Алтайский государственный технический университет имени И. И. Ползунова, Барнаул, 2012. 19 с.

DOI: https://doi.org/10.15407/pmach2023.02.039

UDC 629.7

CRITERION BASIS FOR ASSESSMENT OF TRANSPORT AIRCRAFTS MODIFICATIONS BY COST INDICATORS

Liudmyla V. Kapitanova
l.kapitanova@khai.edu
ORCID: 0000-0003-3878-6734

Danylo S. Kirnosov
d.s.kirnosov@khai.edu
ORCID: 0000-0002-2288-2863

Viktor I. Riabkov
2506lulu@gmail.com
ORCID: 0000-0001-6512-052X

National Aerospace University
"Kharkiv Aviation Institute"
17, Chkalov str., Kharkov,
61070, Ukraine

The subject of research in the paper is the process of forming a criterion base to evaluate the effectiveness of carrying out modification changes in a transport category aircraft. The goal is to develop supporting criteria for making decisions regarding the expediency of modification changes, namely, during design, during production, and at the stage of its operation, at each stage of the life cycle of a new transport category aircraft. The complexity of the task lies in the need to develop a model for evaluation of the consequences of changing the aircraft for each stage separately, which would collectively determine the integral effectiveness of its modification. To evaluate the efficiency of basic aircrafts in operation, there are a number of economic indicators of their efficiency, in particular, the cost of an aircraft hour and the transportation of one ton of cargo per one kilometer, which are only partially taken into account when analyzing the efficiency of aircraft modifications, although in the case of aircraft transport category, specific cost criteria for the entire life cycle both for the base aircraft and for its modification is required. For their development, a method of estimating the cost of the entire life cycle of the aircraft is proposed, as well as a method of dividing modification changes according to the parameters of the upper level (PMD), which is used at the stage of designing the devices, and the lower level (PPO) for the operational stage. On the basis of and taking into account the specifics of the specified methods, indicators of additional labor costs that arise during the implementation of modification changes in the conditions of production and at the stage of aircraft operation have been developed. The proposed criteria take into account indicators of the transport efficiency of heavy aircraft modifications and the integral efficiency of the modification, taking into account the costs at all the main stages of the life cycle of the modification. The scientific novelty of the obtained results is as follows: the supporting criteria for the adoption of decisions regarding the expediency of modification changes at each stage of the life cycle of a new transport category aircraft are proposed, i.e. during design, under the conditions of production and at the stage of its operation. Such criteria will ensure the integral efficiency of the transport aircraft modification.

***Keywords**: transport aircraft, base aircraft, aircraft modifications, aircraft efficiency assessment models.*

Introduction

The process of creating modifications of transport aircrafts of all weight categories has developed widely. On the basis of the changes, the problem of continuously improving the productivity (flight and hour one) of this type of aircrafts is solved.

This goal can be achieved by increasing three parameters: commercial load m_{cl}, distance of transportation L and cruising speed V_{cruise}.

In heavy transport aircrafts, the value of these parameters has usually already been achieved, and when creating modifications, other goals are set and implemented: reducing the mass of structural elements, reducing labor costs in the production process, reducing costs per unit of useful work, reducing costs at the stage of operation, which leads to the need to develop special models of their assessment.

Analysis of recent studies and papers

The creation of heavy transport aircrafts is a feature of the Ukrainian school of aircraft construction: An-132D, An-22, An-124, An-225 [1]. The excellence of their flight and technical characteristics is recognized all over the world, so they are still regularly used.

Of course, the most important indicator for aircrafts is their economic efficiency, laid down by O. Antonov [2] even during the design and production process.

This approach is based on the earlier developments of domestic researchers on the economics of transport category aircrafts at the stage of their operation, which forces developers to look for optimal solutions at the design stage [3].

Taking into account such circumstances, the State Enterprise Antonov [4] has developed a methodology to evaluate decisions based on a set of flight-technical and cost indicators, which is fully implemented during the creation of modifications of transport category aircrafts [6] with increased flight and hourly productivity.

When solving tasks of this type, prognostic models are most often used [5] with an assessment of the economic efficiency of the developed aircrafts at the time of their commissioning and for some subsequent period [6].

The study [7] provides models for evaluation of the economic efficiency when making modifications to the transport aircraft structure. The paper [8] presents an analysis of operational and economic indicators of transport category aircrafts for various purposes, data on reliability, the main reasons for aircrafts failure, engines and components.

In the studies, indicators of economic efficiency were compared with individual flight technical parameters.

With regard to newly created modifications, the method of their specific evaluation according to cost indicators was first presented in paper [9] for short-haul passenger aircrafts.

Parameters that change in the processes of creation and operation of transport aircrafts modification

The classification of parameters characterizing the modification of a transport category aircraft is given in papers [1, 2]. According to it, there are two large classes of variable parameters – PMD and PPO.

They differ in their impact on changes in the starting mass of modification and implementation at different stages of the life cycle:

– PMD – a group of control parameters (upper level $(CP)^u$), that are modified during design, the change of which leads to an increase in the starting mass compared to the mass of the base aircraft (m_0^m (PMD)> m_0^b);

– PPO – a group of control parameters (lower level $(CP)_l$) that change at the stages of production and operation and do not lead to a change in the starting mass (m_0^m (PMD)= m_0^b).

Adequately to their status, a scheme of decision-making supporting criteria throughout the life cycle of the modification, taking into account integral indicators of its effectiveness, has been formed (Fig. 1).

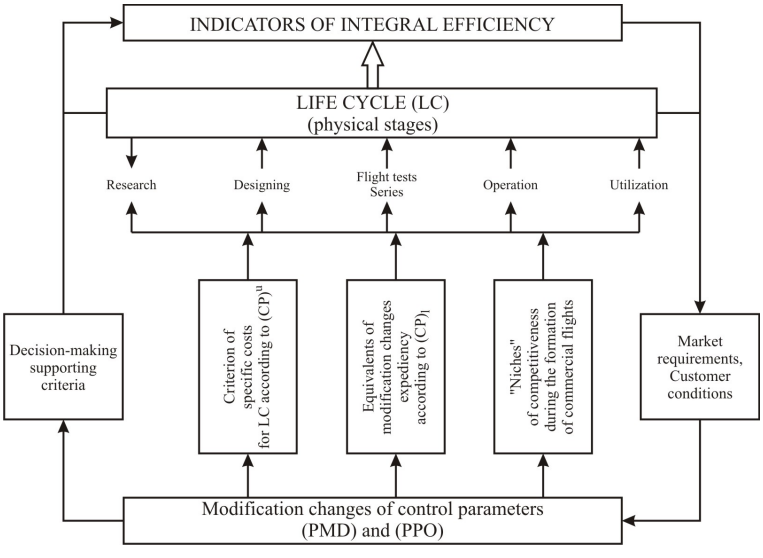

Fig. 1. Decision-making supporting criteria in the structure of stages of the modifications life cycle

From the data shown in the figure, it follows that decision making according to the criterion of specific costs must be carried out at the design stage as calculation PMD parameters, such as life cycle cost, modification performance and calendar resource, which are laid down for the main power elements, are obtained. This approach will reduce the number of options that will be considered at the next stages.

For the stages of the modification production and operation (taking into account the change of the PPO parameters, weight and cost equivalence models of parameters, which are used in the general scheme of evaluation of the modification according to integral indicators of efficiency, are required.

Integral criterion of cost effectiveness of modification changes

As already mentioned, the integral indicators of a heavy aircraft are:

– the total useful work performed by the modification during the operational phase;

– full value costs for the modification life cycle.

In this case, their relation acquires the status of a criterion of integral efficiency:

$$\overline{B}_{\text{lc}} = \frac{\text{full life cycle coast}}{\text{the entire operation of the aircraft during the operational stages}}. \quad (1)$$

This criterion in parametric expression has the form:

$$\overline{B}_{\text{lc}} = \frac{B_{\text{lc}}}{m_{\text{cl}} \cdot L \cdot N}; \quad (2)$$

$$B_{\text{lc}} = A_{\text{t}} \cdot T_{\text{h}}, \quad (3)$$

where T_{h} – declared resource in flight hours; N – the number of flights per life cycle with average flight times; A_{t} is determined by the average costs per flight time, taking into account all phases of the life cycle.

$$A_{\text{t}} = A_{\text{ad}} + A_{\text{ed}} + A_{\text{am}} + A_{\text{em}} + A_{\text{fuel}} + A_{\text{s}} + B_{\text{ap}}, \quad (4)$$

where A_{ad}, A_{ed} – aircraft and engine depreciation costs; A_{am}, A_{em} – aircraft and engine maintenance costs; A_{fuel} – fuel costs; A_{s} – crew salary expenses; B_{ap} – indirect (airport) costs.

The complete work performed by the modification during its life cycle at the stage of its operation is estimated by the expression

$$W = m_{\text{cl}} \cdot L \cdot N, \quad (5)$$

where $m_{\text{cl}} \cdot L$ is the useful work done by the modification in one flight.

Thus, the decision-making supporting criterion for the implementation of modification changes of the main parameters of the modification will be written in the form

$$\overline{B}_{\text{lc}} = \frac{A_{\text{h}}(A_{\text{ad}}, A_{\text{ed}}, A_{\text{am}}, A_{\text{em}}, A_{\text{fuel}}, A_{\text{s}}, B_{\text{ap}}) \cdot T_{\text{h}}}{m_{\text{cl}} \cdot L \cdot N}. \quad (6)$$

Criterion (6) should be classified as an integral group. The dimensionality of the criterion [UAH (USD)/kg × km/flight] fully confirms its integrality, since it includes the amount of commercial load m_{cl}, the distance of transportation L, that is, the main distinguishing feature of the modification (its flight performance) and the declared resource T_{h}. In addition, based on this criterion, it becomes possible to evaluate the effectiveness of the first group of modifiable PMD parameters.

During the life cycle, there are also changes in the second group of parameters (PPO), which do not lead to an increase in the take-off mass of the aircraft, but instead improve some parameters at the expense of others, which is usually accompanied by an increase in labor costs ΔT_0 on the implementation of such processes and leads to a change in cost indicators: flight hours A_{h} and cost of air transportation a.

Taking into account such circumstances, there is a need to develop models of the type

$$a', A'_{\text{h}} = f(\Delta m_{\text{cl}}, \Delta T_0). \quad (7)$$

Naturally, the cost of air transportation a' and the cost of an aircraft hour A'_{h} after such modification changes significantly depend on the ratio of parameters in the right-hand side of the expression (7) $\Delta m_{\text{cl}}/\Delta T_0$ at $\Delta m_{\text{cl}} \neq 0$ and $\Delta T_0 \neq 0$.

Modification changes of PPO parameters include:

– unification of the design of the modification and the base aircraft;

– commercial conversion of the aircraft for seasonal air transportation;

– reducing the number of failures and increasing the reliability of the modified design, etc.

Fig. 2 shows the scheme for obtaining weight equivalents of the expediency of modification changes in PPO parameters.

At the same time, all modification changes are recognized as appropriate in the economic sense, if they lead to a decrease in the cost of an aircraft hour

$$A_{\text{h}} = \Delta a \cdot m_{\text{cl}} \cdot V_{\text{cruise}}, \tag{8}$$

or life cycle cost

$$B_{\text{lc}} = a' \cdot m_{\text{cl}} \cdot V_{\text{cruise}} \cdot B_{\text{af}} \cdot T_{\text{h}}, \tag{9}$$

where V_{cruise} – cruise speed; B_{af} – annual flight in hours; T_{h} – calendar (declared) resource in hours.

Thus, the expediency of modification changes of the PVE is determined by the angle of inclination α of the dependence $\Delta m_{\text{cl}}(\Delta T_0)$

$$\text{arctg}\alpha \to \max, \tag{10}$$

which, in turn, determines the decision-making supporting criteria in the form of equivalents:

$$\left\{\begin{matrix}\Delta m_{\text{cl}}, \Delta T_0 \\ B_{\text{lc}}\end{matrix}\right\} \quad \to \frac{\Delta m_{\text{cl}}}{\Delta T_0}(a' \le a) \to \text{I – advisable to change} \tag{11}$$

$$\to \frac{\Delta m_{\text{cl}}}{\Delta T_0}(a' > a) \to \text{II – not advisable to change} \tag{12}$$

The specificity of criteria (11) and (12) is that the decision is made regarding Δm_{cl}, that is, according to those parameters that the designer can influence under the conditions $a'<a$ and thereby economically justify the effectiveness of the decisions made.

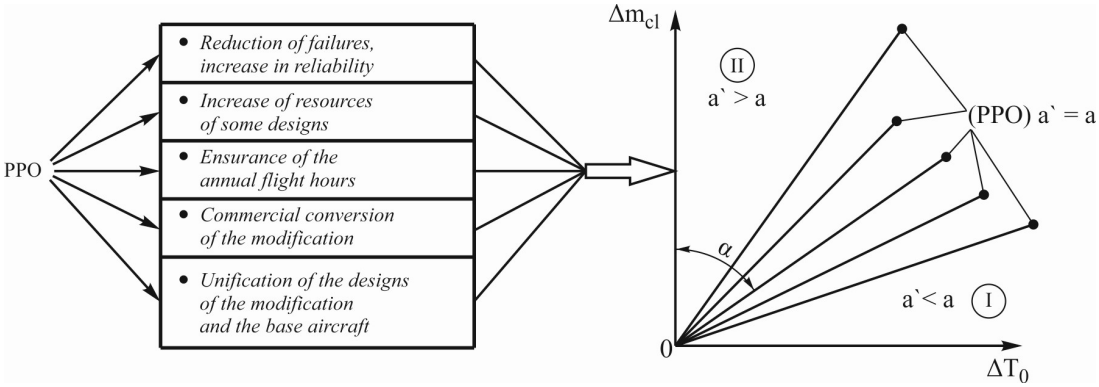

Fig. 2. Graphic representation of the limits of expediency of modification changes by condition $\Delta m_{cl}(\Delta T_0)$:
ΔT_0 – additional labor costs;
a, a' – the cost of air transportation of 1 ton of cargo per 1 km of the route before and after changes in PPO

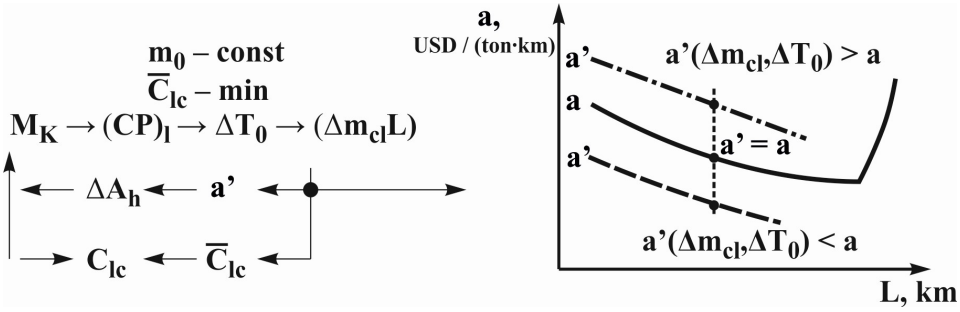

Fig. 3. Scheme of the influence of the main parameters on the change in the cost of air transportation (USD/ton·km) of the basic option and additional labor costs ΔT_0 on a' (USD/ton·km) when changing PPO

In addition, the "more/less" sign defines the limits of possible solutions, equivalently suitable for evaluating the effectiveness of changing parameters regardless of their category and for aircrafts of different purposes.

The implementation of criteria (11) and (12) is associated with specific modification changes and for specific aircrafts with different indicators of labor costs ΔT_0 and commercial load Δm_{cl}. Based on this, efficiency equivalents must be developed for each specific type of aircraft and conditions of its production.

The most generalized (which reflects all combinations of modification changes) is the criterion of specific costs for the full life cycle of the modification $\overline{B}_{\text{lc}}$. It describes the monetary costs incurred per unit of useful work performed by the modification at the stage of its operation.

Values of $\overline{B}_{\text{lc}}$ were determined on the basis of passport data of domestic aircrafts, declared at the time of their commissioning.

Its index score is given as a parameter [USD / (m_{cl}·L·N)], where m_{cl} – mass of the commercial load transported (in tons); L – transportation distance (in km); N– number of flights per life cycle. The results of the numerical evaluation are given in the table. The most effective ones are modifications with a minimum value $\overline{B}_{\text{lc}}$.

When comparing regional passenger and transport aircrafts, it should be recognized that aircrafts modifications have a criterion of specific costs $\overline{B}_{\text{lc}}$ that is slightly worse than the modifications of the An-148-100 aircraft.

Table. Results of a numerical evaluation of the criterion of specific costs for the full life cycle of aircrafts modification

Aircraft type	An-26	An-32	An-132U	An-124-175	An-124-200	An-124-355	An-148-100	An-148	An-148-100M
$\overline{B}_{\text{lc}}$, [USD / (m_{cl}·L·N)]	0.62	0.61	0.51	0.59	0.63	0.62	0.50	0.48	0.85

At the same time, it should be noted that the value of such indicators of transport aircrafts as An-32 and An-132U is somewhat worse than that of modifications of the heavy transport aircraft An-132. This is explained by the insufficiently high resource and short length of the airlines on which they are operated.

Conclusions

1. A criterion base for decision-making support based on the cost integral indicator of the effectiveness of the implementation of modification changes of PMD parameters that change at the general design stage and PPO parameters that change at the production and operation stages, i.e. by the sum of all stages of the life cycle, has been formed.

2. The structure of decision-making supporting criteria is formed by:

– indicators of transport efficiency of heavy aircraft modifications;

– criteria for the integral efficiency of the modification, taking into account the value and additional labor costs ΔT_0 at the main stages of the life cycle.

3. New decision-making supporting criteria in the procedure for evaluating the effectiveness of modification changes are proposed:

– for the stage of modifications development – the criterion of specific costs for the life cycle $\overline{B}_{\text{lc}}$, which is based on the ratio of all types of costs to all useful work, performed by the modification at the stage of its operation;

– for the stage of production and subsequent improvements - criteria for the expediency of modification changes, taking into account the labor costs for their implementation $\left(\frac{\Delta m_{\text{lc}}}{\Delta T_0}(a' \le a)\right)$;

– for the stage of operation of transport aircraft modifications - a method of information presentation of commercial flights in the form of competitiveness indicators [7].

The use of such a set of criteria in relation to modification changes on domestic aircrafts showed that their application significantly reduces the options for modification changes that are considered and reduces the level of subjectivity in their implementation.

References

1. Antonov, O. K. & Tolmachev, V. I. (1966). *Transportnyy samolet segodnya i zavtra* [Transport aircraft today and tomorrow]. *Aviatsiya i kosmonavtika – Aviation and astronautics*, no. 8, pp. 18–25 (in Russian).
2. Antonov, O. K. & Tolmachev, V. I. (1973). *Osnovnyye problemy sozdaniya tyazhelogo dalnego transportnogo samoleta* [The main problems of creating a heavy long-range transport aircraft]: a technical report no. 14526. O. K. Antonov Experienced design office (in Russian).
3. Andriyenko, Yu. G. & Miroshnikov, A. V. (1984). *Vremennaya mezhvedomstvennaya metodika otsenki sravnitelnoy ekonomicheskoy effektivnosti perspektivnykh samoletov grazhdanskoy aviatsii* [Temporary interdepartmental methodology for assessing the comparative economic efficiency of promising civil aviation aircraft]. Moscow: Vozdushnyy transport, 203 p. (in Russian).
4. Andriyenko, Yu. G. (2002). *Metod formirovaniya sovokupnosti tekhniko-ekonomicheskikh kharakteristik v protsedure vybora proyektnykh resheniy pri razrabotke transportnykh samoletov* [The method of forming a set of technical and economic characteristics in the procedure for choosing design solutions in the development of transport aircraft]. *Otkrytyye informatsionnyye i kompyuternyye integrirovannyye tekhnologii – Open information and computer integrated technologies*: Collection of scientific works of National Aerospace University "Kharkiv Aviation Institute", iss. 12, pp. 125–138 (in Russian).
5. Klochkov, V. V., Nizhnik, M. V., & Rusanova, A. L. (2009). Forecasting the cost benefit of developing new modes of rapid passenger transport. *Studies on Russian Economic Development*, vol. 20, iss. 3, pp. 268–280. https://doi.org/10.1134/S1075700709030058.
6. (2013). Current market outlook 2013–2032. The Boeing Company, 42 p. URL: https://www.iaa.ie/docs/default-source/misc/boeing_current_market_outlook_20131.pdf.
7. Ignatyevs, S, Makushkin, S, & Spivakovskyy, S. (2021). Economic feasibility of modifications to the design of transport aircraft. *INCAS Bulletin*, vol. 13, special iss., pp. 67–76. https://doi.org/10.13111/2066-8201.2021.13.S.7.
8. Syam, S. & Jagathy Ray, V. P. (2013). Airworthiness – monitoring of modifications on aircraft, engines & components. *International Journal of Operations and Quantitative Management*, vol. 19, iss. 3, pp. 201–220.
9. Babenko, Yu. V. (2015). *Formirovaniye tarifov na aviaperevozki s uchetom udelnykh zatrat za zhiznennyy tsikl modifikatsiy tyazhelogo transportnogo samoleta* [Formation of tariffs for air transportation, taking into account unit costs for the life cycle of modifications of a heavy transport aircraft]. *Aviatsionno-kosmicheskaya tekhnika i tekhnologiya – Aerospace Engineering and Technology*, no. 10 (127), pp. 124–128 (in Russian).

Received 19 April 2023

Критеріальні основи оцінювання модифікацій транспорних літаків за вартісними показниками

Л. В. Капітанова, Д. С. Кірносов, В. І. Рябков

Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут»,
61070, Україна, Харків, вул. Чкалова, 17

Предметом досліджень у статті обрано процес формування критеріальної бази для оцінки ефективності проведення модифікаційних змін у літаку транспортної категорії. Метою є розробка критеріїв підтримки прийняття на кожному з етапів життєвого циклу нового літака транспортної категорії рішень щодо доцільності модифікаційних змін, а саме: при проєктуванні, при виробництві та на етапі його експлуатації. Складність задачі полягає в необхідності розробки для кожного етапу окремо моделі оцінки наслідків змінення літака, що у сукупності визначала б інтегральну ефективність його модифікації. Для оцінки ефективності базових літаків, що знаходяться в експлуатації, існує ряд економічних показників їх ефективності, зокрема, вартість літако-години і перевезення однієї тонни вантажу на один кілометр, що лише частково беруться до уваги при аналізі ефективності модифікацій літака, хоча у випадку з літаками транспортної категорії потрібні критерії питомих витрат за весь життєвий цикл як для базового літака, так і для його модифікації. Для їх розробки пропонується метод оцінки вартості усього життєвого циклу літака, а також метод поділу модифікаційних змін за параметрами верхнього рівня (ПМП), який застосовується на етапі проєктування апаратів, і нижнього рівня для етапу експлуатації (ПВЕ). На основі й з урахуванням специфіки вказаних методів розроблено показники додаткових трудовитрат, які виникають при реалізації модифікаційних змін в умовах виробництва й на етапі експлуатації літака. У запропонованих критеріях враховано показники транспортної ефективності модифікацій важкого літака й інтегральної ефективності модифікації з урахуванням вартісних

витрат на усіх основних етапах життєвого циклу модифікації. Наукова новизна отриманих результатів полягає в наступному: запропоновано критерії підтримки прийняття на кожному з етапів життєвого циклу нового літака транспортної категорії рішень щодо доцільності модифікаційних змін, тобто при проєктуванні, в умовах виробництва і на етапі її експлуатації. Такі критерії забезпечать інтегральну ефективність модифікації транспортного літака.

***Ключові слова**: транспортний літак, базовий літак, модифікації літака, моделі оцінки ефективності літака.*

Література

1. Антонов О. К., Толмачев В. И. Транспортный самолет сегодня и завтра. Авиация и космонавтика. 1966. № 8. С. 18–25.
2. Антонов О. К., Толмачев В. И. Основные проблемы создания тяжелого дальнего транспортного самолета: технический отчет № 14526. ОКБ имени О. К. Антонова. 1973.
3. Андриенко Ю. Г., Мирошников А. В. Временная межведомственная методика оценки сравнительной экономической эффективности перспективных самолетов гражданской авиации. М.: Воздушный транспорт, 1984. 203 с.
4. Андриенко Ю. Г. Метод формирования совокупности технико-экономических характеристик в процедуре выбора проектных решений при разработке транспортных самолетов. *Открытые информационные и компьютерные интегрированные технологии*: сб. науч. тр. Харьк. Нац. аэрокосм. ун-та «ХАИ». 2002. Вып. 12. С. 125–138.
5. Клочков В. В., Нижник М. В., Русанова А. Л. Прогнозирование экономической эффективности создания новых видов скоростного пассажирского транспорта. *Проблемы прогнозирования*. 2009. № 3. С. 58–76.
6. Current market outlook 2013–2032. The Boeing Company, 2013. 42 p. URL: https://www.iaa.ie/docs/default-source/misc/boeing_current_market_outlook_20131.pdf.
7. Ignatyevs S, Makushkin S, Spivakovskyy S. Economic feasibility of modifications to the design of transport aircraft. *INCAS Bulletin*. 2021. Vol. 13. Special Iss. P. 67–76. https://doi.org/10.13111/2066-8201.2021.13.S.7.
8. Syam S., Jagathy Ray V. P. Airworthiness – monitoring of modifications on aircraft, engines & components. *International Journal of Operations and Quantitative Management*. 2013. Vol. 19. Iss. 3. P. 201–220.
9. Бабенко Ю. В. Формирование тарифов на авиаперевозки с учетом удельных затрат за жизненный цикл модификаций тяжелого транспортного самолета. *Авиационно-космическая техника и технология*. 2015. № 10 (127). С. 124–128.