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DECISION SUPPORT MODELING IN THE PROCEDURE OF INCREASING LOAD CAPACITY AND FLIGHT EFFICIENCY OF TRANSPORT CATEGORY AIRCRAFT MODIFICATIONS

Enhancing flight efficiency is a pressing issue in the development of the aircraft manufacturing industry. Aircraft manufacturers in Europe, the USA, China, and Ukraine are following this path of improvement for such aircraft, as it is the most economically efficient approach. This method significantly reduces the time required for design, prototype production, flight testing, and the start of operation of the first units. At the National Aerospace University "KhAI", the Department of Aircraft and Helicopter Design has established a school focused on implementing necessary modification changes in transport category aircraft. The distinctive feature of this approach is that only outdated parameters of a well-proven baseline aircraft are modified, while the majority of the parameters are carried over to the modification from the original version. This foundation underpins the research presented in this publication. ***The research aims*** *to develop parametric models to support decision-making during the preliminary design stage for enhancing the load capacity and flight efficiency of transport category aircraft modifications.* ***Research methods:*** *a method of changes assessing in wing induced drag with modifications in its planform shape; a method of "payload-range" characteristics creation.* ***The object of the research*** *is the development of parametric models to support decision-making during the preliminary design stage of transport category aircraft modifications. The following results were obtained a package of models was developed, including: ensuring the specified load capacity and "payload-range" characteristics; a temporal model of parameter changes in modifications considering the time frame for modifications; cost indicators for changes at individual stages and throughout the entire life cycle; representation of modifications in terms of their competitiveness; formation of wing geometric shapes with minimal induced drag at a given lift; ensuring that the takeoff and landing characteristics of modifications remain at the level of the baseline aircraft; coordination of wing lift coefficients and engine throttle characteristics to ensure minimum fuel consumption in cruise flight mode. Each model serves as a tool to address the main tasks of increasing load capacity and the range of useful payload transport at the moment of modification introduction and throughout its entire life cycle. Examples of real modification changes in domestic transport aircraft, such as the An-32, An-32B, and An-132U, demonstrate that using the proposed decision support models during the preliminary design stage has ensured their competitiveness throughout their operational life.* ***Practical significance of the obtained results****: Based on the developed models, the load capacity and flight efficiency of modifications like the An-32 and An-32B have been increased, and the parameters of the An-132U modification with Motor Sich engines have been optimized, surpassing the load capacity and flight efficiency of all other analogs of light military transport aircraft.* ***Scientific novelty of the obtained results****: For the first time, a method was developed to minimize induced drag during cruise flight with the required lift force, i.e., for a given load, allowing an increase in the range of modified aircraft.*

Keywords*: aircraft modifications; transport category aircraft modifications; aircraft load capacity; "payload-range" characteristic.*

1. Introduction

In the modification process, as in science, there are two recognized methods: the modular method and the method of reserving.

The modular design method involves the simultaneous development of a family of aircraft with identical values of many key parameters, based on common solutions in aerodynamics, layout, equipment, control systems, structures, and technology.

In this approach, the aircraft family is essentially formed from standardized structural components, interchangeable assemblies, and systems that perform similar functions. Only those parts of the structure that distinguish each modification from the baseline aircraft are not standardized.

Advantages of this method include retaining the entire internal layout, cockpit, wiring, and equipment integration; control systems and all principal aircraft system schematics are largely preserved, and sometimes even the powerplant. Under these conditions, development costs represent only a small fraction of the total cost of developing the baseline aircraft.

As a distinctive scientific approach, the method of modifications design based on reserving should be recognized.

This method involves selecting certain aircraft parameters with a predetermined technically and economically reasonable excess to create potential for modification changes.

However, developing modifications using this method presents a certain contradiction: on one hand, planned reserves add weight to the structure, hindering maximum efficiency; on the other hand, their absence complicates the task of modifying the baseline aircraft. It is known that enhancing one valuable quality of an aircraft usually comes at the expense of another; hence, decision support models are indispensable in this process.

1.1. Analysis of literary sources and research problem definition

The design of modifications is carried out in accordance with the standards and regulations adopted in Ukraine [1] and foreign countries.

The Legislative Aviation Code [1] describes the rules for operating aircraft in Ukraine, the implementation of which makes it possible to ensure flight safety. However, this source does not stipulate the condition for achieving such a goal by design and construction.

Since this work considers the process of creating a modification for a transport category aircraft, it is naturally based on the legislative framework established by the Air Code of Ukraine and the Flightworthiness Maps ARU-25 [2]. .

The regulatory documents for light aircraft [2] and for the transport category [3] establish the rules for the creation of transport category aircraft, taking into account the specifics of their operation at airfields of various classes, recognized in various countries. But in this case it is not described how to achieve such a goal using variations in aircraft parameters.

The same drawback is also responsible for shortcomings in aviation regulations [4, 5] for aircraft for various purposes.

The regulatory document [6] presents aircraft engines and the conditions for their installation on an aircraft. However, it is not described with the help of which modes of their operation it is possible to achieve the required efficiency of the airframe-engine system.

In English-language publications [7, 8], the topic of efficiency is also a priority, especially at the aircraft design stage.

In work [9], methods and partially implemented models for the design of military transport aircraft developed in Ukraine are proposed. These models are also mandatory, as they are published in official documents of the state enterprise "Antonov". However, models for supporting decision-making at the early stages of modification design, when most of the key parameters are still unknown, are not presented.

The originality of publication [10] lies in the fact that it first addressed and partially solved the task of reducing computational time costs in the context of multidisciplinary optimization of the design of a typical medium-range aircraft. This was investigated by assessing active constraints and using multipoint models for resistance and structural stress evaluation. Solving this problem allows the rapid introduction of a modification with increased operational performance. However, this article provides no data on how much time is actually saved in the introduction of a new modification by using decision-support models at the early stages of the computational process when forming the main parameters of the new modification.

In publication [11], high-precision aero-structural optimization of a transport aircraft is studied. The article develops models for optimizing geometric shapes, which lead to significant changes in the aerodynamic quality of the aircraft and, naturally, to an increase in the range with payload in the basic version. However, recommendations regarding the simultaneous increase in load capacity and flight range, as well as for transporting increased mass, are not provided in this work.

Publication [12] discusses the limitation of modification changes in the aircraft wing to avoid flutter phenomena. However, this article does not link flutter processes with the "payload-range" transport characteristic, i.e., with the key parameters accepted at the earliest stage of modification design.

Work [13] investigates the important requirement of minimizing fuel consumption when changing the aerodynamic forms of an aircraft using the scheme: general appearance of the base aircraft → aerodynamic quality → fuel efficiency. This scheme allows for an evaluation of the fuel efficiency of an already designed aircraft. However, it is not suitable for the earliest stage of preliminary formation of the necessary main modification changes.

The information source [14] partially addresses the important issue of evaluating the costs of implementing modifications in transport category aircraft in monetary terms. In this case:

- only direct costs are considered;

- models for specific costs per ton of cargo per kilometer are not provided, i.e., no specific cost indicator that takes flight performance into account is introduced, and the "payload-range" characteristic of the newly created modification is not considered.

The need to introduce such indicator is raised in work [15]. It formulates the problem, but no criteria for decision-making at the earliest stages of modification design, when most parameters of the new aircraft are still unknown, are provided.

In work [16], an important but very specific issue regarding the feasibility of creating a twin-fuselage modification of a passenger aircraft is discussed, with fuel efficiency used as the feasibility criterion. This is a very important indicator, but the work does not clearly define which modification changes, especially in the powerplant, led to it. Therefore, this approach cannot be considered universal or applicable when considering modification changes of other types.

When implementing modification changes in the wing, fuselage, and power plant, the issue of reassessing the modification's mass and balance parameters inevitably arises.

Work [17] addresses an approach of assessing these important parameters, but it does not address the influence of changes in the modification's balance on the "payload-range" transport characteristic, i.e., the operational performance of the modification.

In case of an increase in flight range with a full commercial load, work [18] presents research on the necessity of changing the useful configuration of the aircraft, which is important when forming the necessary modification changes in the aircraft assemblies. However, models supporting such decisions are not presented in this publication.

The research presented in work [19] is notable in that it highlights the necessity of modeling the placement of commercial cargo within the fuselage, considering balance limitations. However, models ensuring that the aircraft flies at the most economical wing angles of attack (in terms of fuel consumption) are not provided, and thus decision-making models for increasing flight range and therefore operational performance are absent.

From the analysis of the literary sources, it follows that the problem of developing decision-support models for increasing load capacity and operational performance at the preliminary design stage of modifications to transport category aircraft has not been addressed and remains a relevant issue today.

1.2. The goal of the research

To develop parametric decision-support models at the preliminary design stage to enhance load capacity and operational performance of modifications to transport category aircraft.

The main areas ensuring the achievement of this goal are:

- parametric modeling of load capacity and operational performance;
- modeling the minimization of induced drag for a given lift force;
- implementing the developed decision-support models through examples of modifications to the An-32, An-32B, and An-132U aircraft.

2. Parametric modeling of load capacity and operational performance at the modification design

Subject of the research: Modifications to transport category aircraft that ensure the required increase in specified load capacity and operational performance with partial changes to their transport characteristics.

Object of the research: Parametric decision-support models at the initial stage of forming the main parameters of modifications to transport category aircraft that ensure the necessary increase in load capacity and operational performance.

The "payload-range" characteristic (Fig. 1) essentially represents one of the most important parameters of both the base aircraft and its modifications, for the sake of which modifications are made: $W = m_{pl}(L)$. At the same time, the payload mass (m_{pl}) is understood as the sum

$$m_{pl} = m_{cargo} + m_{pass}. \quad (1)$$

Point A on the diagram (Fig. 1) corresponds to the maximum target payload, determined from the aircraft's weight balance equation, where 0D is the maximum range, 0A is the maximum useful load, AB is the range at maximum load, OK is the cargo mass, KN represents the cargo limitation, and A'B' represents the resource limitation.

Point B corresponds to the maximum range with maximum target payload, according to cruise flight conditions and fuel reserve norms. Increasing the range is only possible by replacing part of the target payload with fuel. At point C, the fuel reserve is limited by the tank capacity, and the operational mass reaches its maximum value.

In such extreme parameters, the "payload-range" characteristic of the aircraft is presented with some limitations at points A and C.

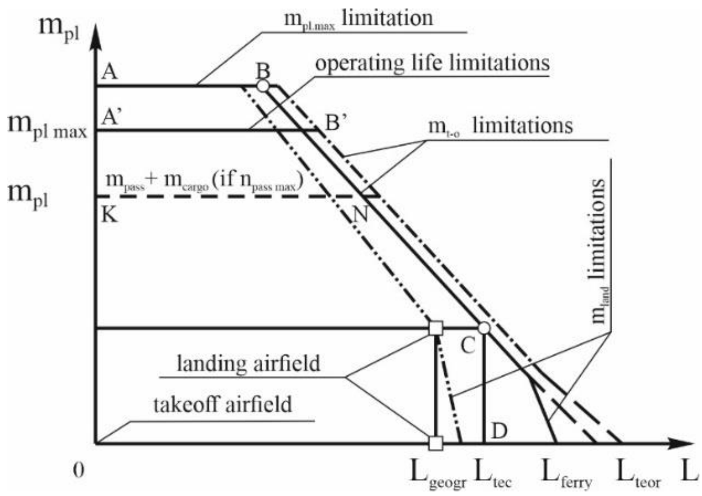

Figure 1. Payload-range dependency variants for a transport aircraft

Further range increase is only possible by reducing takeoff mass, and thus, hourly fuel consumption, which leads to a sharp reduction in target payload. At point D, the cargo mass is zero, which corresponds to the case of maximum range without commercial payload, usually used to evaluate the aircraft's cruise range.

The sloped part of the "payload-range" diagram characterizes aircraft analogs based on aerodynamic quality "K" and propulsion efficiency based on specific fuel consumption "C_e". These parameters are part of the calculation dependencies that determine the range [9]:

$$L = 3.6 \int_{m_{final}}^{m_{start}} \frac{VK}{C_e} \frac{dm}{m}, \tag{2}$$

and flight duration is determined by the expression:

$$t_p = 3.6 \int_{m_{final}}^{m_{start}} \frac{K}{C_e} \frac{dm}{m}, \tag{3}$$

where m_{start}, m_{final} are the aircraft's mass at the start and end of the cruise flight.

The parameters in equations (2) and (3) depend on other coordination parameters. Considering this, range L is evaluated using the Breguet formula for turbojet aircraft [9]:

$$L = \frac{KV_{flight}}{C_R} \lambda n \frac{1}{1-\overline{\overline{m}}_{fuel}}, \tag{4}$$

where L is the range, V_{flight} is the cruise speed, K is the aerodynamic efficiency, C_R is the fuel consumption, and $\overline{m}_{fuel}$ is the relative fuel mass.

Thus, the system represents a decision support model for a multiparametric problem aimed at ensuring the required "payload-range" characteristic of the designed modification:

$$\begin{Bmatrix} m_{pl} = m_0 - m_{airframe} - m_{fuel} \\ L = \dfrac{KV_{flight}}{C_R} \lambda n \dfrac{1}{1-\overline{\overline{m}}_{fuel}} \end{Bmatrix}. \tag{5}$$

In this formulation, the characteristic shown in Fig. 1, in parametric form, represents the useful work performed by the aircraft during one flight. To assess flight performance, it is necessary to introduce the time factor into the proposed model, as well as the specifics of cruising flight mode.

3. Minimization of induced drag at a given lift force

The lift capability of wings with moderate and large aspect ratios (λ >3) at subsonic flight speeds with attached flow is characterized by the lift coefficient and its derivative with respect to the angle of attack [10]:

$$C_{angle} = C^{\alpha}_{angle}(\alpha - \alpha_0), \tag{6}$$

where α_0 – the angle of attack at C_{angle} =0 at subsonic flight speeds can be expressed as:

$$C^{\alpha}_{angle} = \frac{\partial C_{angle}}{\partial \alpha} = 2\pi = \frac{\lambda}{\overline{p}\lambda + 2}, \tag{7}$$

where $\overline{p}$ is the ratio of the wing's semi-perimeter to its span, which is determined by the geometry of the trapezoidal wing in planform [9]:

$$\overline{p} = \frac{1}{2}\left(\frac{1}{\cos\chi_{l.e}} + \frac{1}{\cos\chi_{t.e}}\right) + \frac{2}{\lambda(\eta+1)}, \tag{8}$$

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where $\chi_{l.e}$ and $\chi_{t.e}$ are, respectively, the leading and trailing edge sweep angles of the wing, which are related to each other as follows:

$$g\chi_{l.e} = tg\chi_{l.e} - \frac{4}{\lambda}\cdot\frac{\eta-1}{\eta+1}. \qquad (9)$$

In generating lift, the geometric shapes must simultaneously ensure the minimum value of the wing's drag [11]:

$$C_x = C_{xo} + C_{xi} = C_{xo} + DC^{\alpha}_{angle}, \qquad (10)$$

where C_{xo} is the drag coefficient, C_{xi} is the induced drag coefficient, and D is the profile drag coefficient, which, in turn, is defined by the following expression:

$$D = \frac{B}{\pi\lambda_{ef}}. \qquad (11)$$

Therefore, the decision support model for minimizing induced drag adopts the following definition of the coefficient:

$$B = 1 + \delta_{instab}, \qquad (12)$$
$$\delta_{instab} = \lambda\left(0.0244 - 0.022\cdot\cos\chi\right).$$

The value of C_{xi} is then estimated by the expression:

$$C_{xi} = \frac{B_{instab}}{\pi\lambda_{ef}}C^2_{angle\ cruise}, \qquad (13)$$

where λ_{ef} is the effective aspect ratio of the wing (Fig. 2).

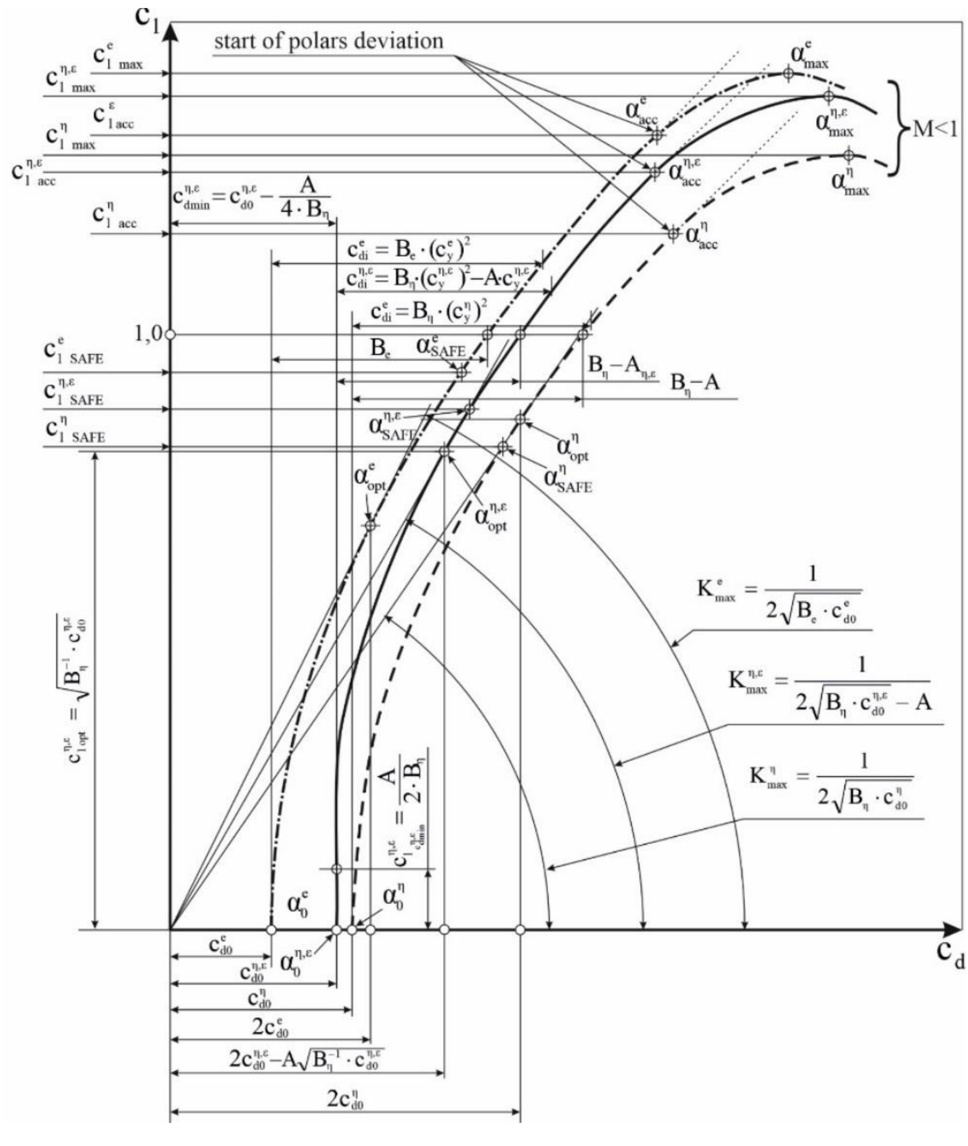

Figure 2. Relationship between aerodynamic efficiency and the magnitude of induced drag C_{xi} during geometric reconfiguration of a wing with medium aspect ratio

In modification changes to the wing, it is important to account for the influence of individual geometric parameters based on this model: wing taper ratio η, the magnitude of the break points $\overline{Z}_{Hi}$, and the angles of geometric twist of the local wing chords ε, on the change in value C_{xi} and the wing's drag polar (see Fig. 2).

For the wing configuration "center section + 2 consoles," computational analysis of the total drag has established (Figure 3) that the value of induced drag C_{xi} ("wing + horizontal stabilizer," shaded area) represents a significant portion of the total drag of the aircraft. Therefore, reducing its value (when $Y_{basic} = Y_{modification}$) during geometric reconfiguration of the wing (with the induced drag coefficient as a key factor) is a relevant task. Minimizing this drag using a decision support model becomes an important tool for ensuring high aerodynamic efficiency at the design stage of the aircraft modification.

As an example, Figure 3 shows the numerical values of various types of drag of major aircraft components, calculated according to the methodology in [9] for a medium-range aircraft with a trapezoidal wing in plan view.

As we can see, C_{xi} (wing + horizontal stabilizer), the shaded areas, constitute a significant portion of the aircraft's overall drag, and therefore, reducing its magnitude has always been and remains an important task.

One effective method of the induced drag coefficient C_{xi} reduction is by deliberately altering the rate of increase in induced drag, or the B_M criterion, through the use of geometric twist of local wing chords along the span.

These results were obtained by solving the problem of minimizing induced drag (C_{xi}) at a given lift coefficient (Cangle). These results show that induced drag C_{xi} makes up a significant portion (approximately 27%) of total drag, and its reduction (at a given Cangle) is an important step during the preliminary modification design phase.

4. Discussion of research results

The discussion focuses on the implementation of decision-support models in the modification of light military transport aircraft, such as the An-32, An-32B, and An-132U. It is noted that the effectiveness of using decision-support models for the An-32 and An-32B aircraft was evaluated based on their parameters achieved during serial production, while the parameters of the An-132U modification were obtained by the authors considering the required operational performance and minimizing the induced drag of the "wing + horizontal stabilizer" system.

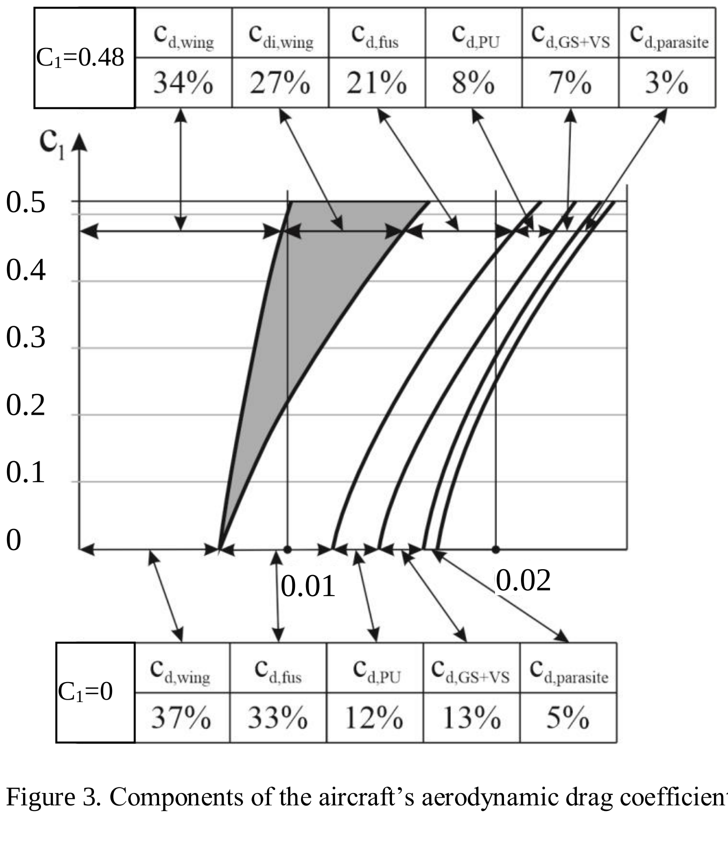

Figure 3. Components of the aircraft's aerodynamic drag coefficient

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Absolute and relative values of this evaluation are shown in Figure 4.

The results demonstrate that using decision-support models during the creation of the An-32 modification based on the An-26 led to a slight increase in operational performance, but the range with full load increased by nearly 50%.

When comparing the An-32B modification to the base An-32 model, there was a significant increase in load capacity from 5.5 tons to 6.7 tons, and the range with full payload increased by 11%.

For the An-132U modification, the payload capacity increased from 6.7 tons (An-32B) to 8.0 tons, which significantly boosted its operational performance (W_{fl}) (see Figure 4, b).

It is also noted that the increased range for carrying full loads in the An-32B and An-132U modifications was facilitated by reducing the induced drag of the "wing + horizontal stabilizer" system.

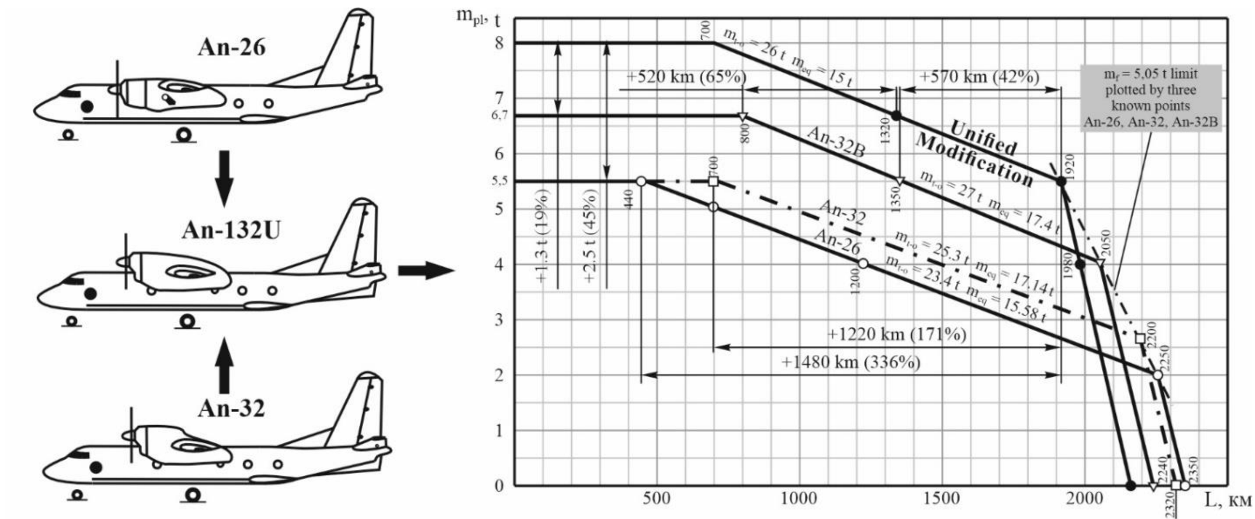
Analyzing these results, it is also important to consider the economic indicators of the modifications, which are presented in Table 4, b. These factors are included in the decision-support structure for the An-32, An-32B, and An-132U modifications, as they represent the costs associated with implementing modification decisions.

Thus, the results shown in Figure 4 convincingly demonstrate the effectiveness of using decision-support models during the preliminary design stage of transport category aircraft modifications when it is necessary to increase their payload capacity and operational performance.

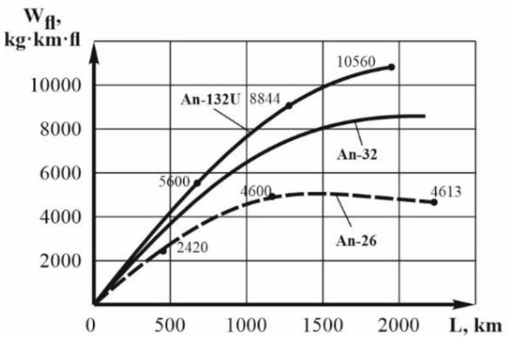
The decision-support models developed in this article for designing transport category aircraft modifications with increased payload capacity (see equation (5)) can also be successfully used in the design of dual-purpose aircraft modifications. This applies both to commercial use and military transport variants.

Due to different requirements for civil and military aircraft, significant changes occur in the masses within the decision-support system (equation (5)). As a result, the fuselage masses in various use cases change significantly, requiring the consideration of these modification changes in evaluating their effectiveness.

The authors conducted such studies in the creation of dual-purpose aircraft, such as the An-32 → An-132D, An-148 → An-178 and An-77 → An-188. These studies demonstrated the economic viability of dual-purpose aircraft.



a)



b)

Modifications / Parameters	An-32B	An-32	An-26	An-132U
Life cycle cost, USD	$735 \cdot 10^5$	$735 \cdot 10^5$	$675 \cdot 10^5$	$100 \cdot 10^6$
Criteria of life cycle specific costs, USD/(t·km·fl)	0.59	0.59	1.55	0.39
Cost of flight hour, USD	2100	2100	2250	2000

c)

Figure 4. Characteristics of payload-range (a), operational performance (b), and efficiency indicators (c) for the An-132U modification

Conclusion

1. A comprehensive structure for the decision-support models package used during the design phase of transport category aircraft modifications is proposed.

2. The package consists of models for:

– ensuring the specified payload and "payload-range" characteristics;

– a temporal model for parameter changes considering the modification's creation timeline;

– cost indicators, both for individual stages and across the entire life cycle;

– representing modifications in terms of competitiveness;

– forming the geometric shapes of the wing with minimal induced drag at a given lift force;

– ensuring the takeoff and landing characteristics of the modifications at the level of the baseline aircraft;

– harmonizing the lift coefficient of the wing with the throttle characteristics of the engine to ensure minimal fuel consumption in cruise flight.

3. The use of this decision-support models package ensures that the designed modification is competitive both at the time of its introduction into operation and throughout its life cycle with the required "payload-range" characteristics.

4. The following models are parameterized in this paper:

– a model for determining the operational performance of the modification by constructing the "payload-range" characteristic;

– a model for reducing the induced drag of the "wing + horizontal stabilizer" system at the necessary wing lift, ensuring high aerodynamic efficiency.

The parametric models obtained were used to analyze the efficiency of modifications to the military transport aircraft An-32, An-32B, and An-132U. It was found that – the modification of the light transport aircraft An-132U by forming the "wing center section + 2 consoles" wing shape minimized induced drag and achieved high aerodynamic efficiency.

5. The results of the An-132U design indicate that:

– payload capacity increased by 12% compared to the improved baseline variants;

– aircraft operating costs per flight hour were reduced by 9%. This result is a convincing example of the effective use of the two developed parametric models during the design stage of modifications.

6. The obtained results confirm that the proposed scientific approach is highly promising, particularly in the design of dual-purpose aircraft modifications.

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МОДЕЛЮВАННЯ ПІДТРИМКИ ПРИЙНЯТТЯ РІШЕНЬ У ПРОЦЕДУРІ ПІДВИЩЕННЯ ВАНТАЖОПІДЙОМНОСТІ ТА РЕЙСОВОЇ ПРОДУКТИВНОСТІ МОДИФІКАЦІЙ ЛІТАКІВ ТРАНСПОРТНОЇ КАТЕГОРІЇ

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Підвищення ефективності польотів є актуальною проблемою розвитку літакобудування. Цим шляхом удосконалення таких літаків йдуть виробники літаків Європи, США, Китаю та України, оскільки це найбільш економічно ефективний підхід. Такий спосіб значно скорочує час на проектування, виготовлення дослідного зразка, льотні випробування та введення в експлуатацію перших екземплярів. У Національному аерокосмічному університеті імені М. Є. Жуковського «ХАІ» на кафедрі проектування літаків та вертольотів створено школу, спрямовану на впровадження необхідних модифікаційних змін у літаках транспортної категорії. Відмінною рисою цього підходу є те, що модифікуються лише застарілі параметри добре перевіреного базового літака, а більшість параметрів переноситься на модифікацію літака з базової версії літака. На цій основі побудовано дослідження, представлені в цій публікації. **Цілі дослідження.** Дослідження спрямоване на розробку параметричних моделей для підтримки прийняття рішень на етапі попереднього проектування щодо підвищення вантажопідйомності, рейсової продуктивності модифікацій літаків транспортної категорії. **Методи дослідження:** метод оцінки зміни індуктивного опору крила при зміні його геометричної форми вигляду в плані; метод побудови характеристик "вантаж - дальність". **Об'єктом дослідження** є розробка параметричних моделей підтримки прийняття рішень на етапі попереднього проектування модифікацій літаків транспортної категорії. Отримано наступні результати, розроблено пакет моделей, що включає: забезпечення заданої вантажопідйомності та характеристик "вантаж - дальність", часова модель змін параметрів у модифікаціях з урахуванням часових рамок для модифікацій; вартісні показники змін як на окремих етапах створення модифікації літака, так і протягом усього життєвого циклу літального апарату; представлення модифікацій літака з точки зору їх конкурентоспроможності; формування геометричних форм крила з мінімальним наведеним індуктивним опором при заданій підйомній силі; забезпечення злітно-посадкових характеристик модифікацій літака на рівні їх характеристик базових літаків; узгодження коефіцієнтів підйомної сили крила і дросельних характеристик двигуна для забезпечення мінімальних витрат палива в крейсерському режимі польоту. Кожна модель є інструментом для забезпечення основних завдань по збільшенню вантажопідйомності та дальності транспортування корисного вантажу на момент впровадження модифікації літака та протягом усього її життєвого циклу. Приклади реальних модифікаційних змін вітчизняних транспортних літаків, таких як Ан-32, Ан-32Б, Ан-132У, демонструють, що використання запропонованих моделей підтримки прийняття рішень на етапі попереднього проектування забезпечило їх конкурентоспроможність літаків протягом усього терміну експлуатації. **Практичне значення отриманих результатів:** На основі розроблених моделей підвищено вантажопідйомність і рейсової продуктивності модифікацій типу Ан-32 і Ан-32Б, а також сформовано параметри модифікації літака Ан-132У з двигунами «Мотор Січ», що перевершують за вантажопідйомністю і рейсовою продуктивністю всі інші аналоги легких військово-транспортних літаків. **Наукова новизна отриманих результатів:** Вперше розроблено метод мінімізації наведеного індуктивного опору під час крейсерського польоту з необхідною підйомною силою, тобто при заданому навантаженні, для збільшення дальності модифікованого літака.

Ключові слова: модифікація літака; модифікацій літака транспортної категорії; вантажопідйомність літака; характеристика літака "вантаж - дальність".

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