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# CONCEPTUAL ASPECT OF MEASURING THE EFFICIENCY OF CARGO UNMANNED AERIAL SYSTEM

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***Abstract***—*This article examines the conceptual framework for measuring the efficiency of unmanned systems, focusing on a task-oriented and problem-solving approach to evaluating the performance of cargo unmanned aerial vehicles. The efficiency of cargo unmanned aerial vehicles pertains to their ability to complete missions on time and cost-effectively, while maximizing utilization, minimizing resource loss, and maintaining an acceptable level of flight safety. It is important to highlight that the efficiency of cargo unmanned aerial vehicles is multifaceted, encompassing technical, operational, economic, environmental, and regulatory dimensions. Progress in each of these areas contributes to the successful deployment and optimization of cargo drones across various applications, from last-mile deliveries to supply chain operations in remote regions. The article presents two methodologies for assessing the efficiency of cargo drones.*

**Index Terms**—Efficiency; cargo unmanned aerial vehicle; unmanned aerial system; integral efficiency; vectors of controlled and uncontrolled variables; reflexive unmanned aerial vehicle life; models with explicit and implicit relationships of system parameters.

## I. INTRODUCTION

The efficiency of cargo drones is the ability of these Unmanned Aerial System (UAS) to perform their tasks cost-effectively and on time, while maximizing their use and minimizing resource losses at an acceptable level of flight safety. The conceptual aspect of measuring the effectiveness of such systems includes, first, the formulation of the task of measuring the effectiveness of UAS and methods for solving it. To do this, it is necessary to emphasize that the efficiency of cargo UAS is multifaceted and includes technological, operational, economic, environmental, and regulatory aspects. Continuous progress in these areas is facilitating the introduction and optimization of cargo UAS for various applications, from last-mile delivery to supply chains in remote areas.

## II. PROBLEM STATEMENT

Therefore, measuring the effectiveness of UAS involves solving a set of separate tasks. Among these tasks, the main task is to formalize different types of effects and their interrelationships. The effectiveness of cargo UAVs can be assessed by several key factors, the main ones being the following (Fig. 1).

The effectiveness of the UAS is also associated with a number of flight restrictions that can significantly affect it. These restrictions can be summarized as follows (Fig. 2).

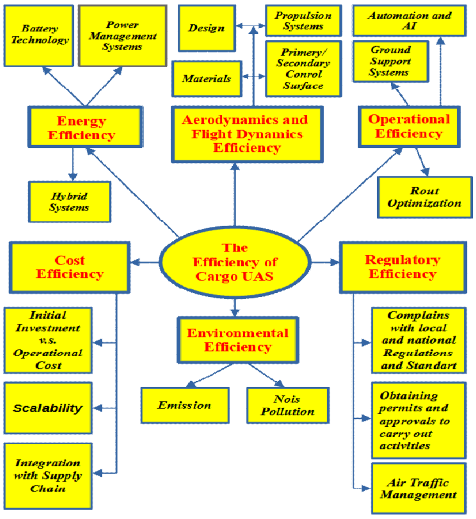


Fig. 1. Key components of efficiency

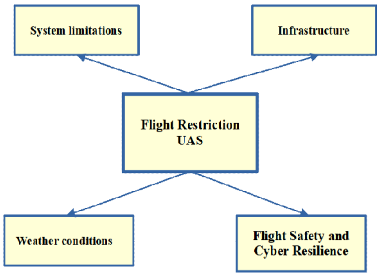


Fig. 2. Restrictions on UAS flights

The task of measuring efficiency mathematically in terms of functional analysis [1] can be formulated in general as follows. Then, in accordance with the parameters of Figs 1 and 2, an unmanned aerial system is characterized by a $g_1$- dimensional vector $\lambda'=\{\lambda'_1,\lambda'_2,\ldots,\lambda'_{g1}\}$ of controlled variables and a $g_2$- dimensional vector $\lambda''=\{\lambda''_1,\lambda''_2,\ldots,\lambda''_{g2}\}$ of uncontrollable variables, and its quality or components of the types of effects that determine the effectiveness of UAS – by a $g$-dimensional vector function:

$$F\{\lambda',\lambda''\}=\{F_i(\lambda',\lambda''),\quad i\in I_g\},\quad I_g=\overline{1,g}.$$

The system efficiency is represented as a vector functional:

$$E_c=\{\varepsilon_j, j\in I_1\},\quad I_1=\overline{1,g},\tag{1}$$

where $\varepsilon_j$ is the indicator of the *j*th effect. Moreover:

$$\varepsilon_j=\varepsilon_j[F(\lambda',\lambda'')].$$

A set of **1** vectors of the type $\varepsilon_j, j=\overline{1,1}$ describes the components of different types of effect of the system under consideration. Then their composition, which has dimension $L=\{1\}$, describes the integral efficiency of the unmanned system.

## III. Proposed Method

When determining the integral efficiency (hereinafter simply the efficiency of the system), two cases can be distinguished, in fact, these are two methods.

*Method 1. The joint (integral) criterion has the following structure*:

$$m=F(\varepsilon_1,\varepsilon_2,\ldots,\varepsilon_j),\quad j=\overline{1,n},$$

where $\varepsilon_j$ is the value of the criterion for the *i*th type of effect (*j*th separate criterion).

This method is convenient due to its relative simplicity and allows comparing different types of UAS by their tactical characteristics, without taking into account the impact of such characteristics on the resulting effect. The scope of this method is a rapid assessment in the task of comparative selection of the best version of the UAS or UAV.

*Method 2. The resulting criterion is represented as a function of the coordinates of the new operation.*

However, it is not a function of individual criteria, as in the first case. This means that the new combined operation has its own objective that is not related to the individual objectives of the individual operations. The combined operation is based only on the assets of the individual operations and does not use the process of deriving a common criterion from the individual ones. Nevertheless, the result is a type diagram:

$$m=F[\varepsilon_1(\varepsilon_2(\varepsilon_1))],$$

that is, there is a "dimensional absorption" due to the corresponding transformations. This means that when we talk about a combined operation and obtaining a common criterion, only the first case is meant. Both of these cases are analyzed below.

Measuring efficiency is reduced to choosing a strategy $F(\lambda',\lambda'')$ from the domain $Q_F$ of its admissible values. The $Q_F$ domain is defined by a set of constraints on individual quality indicators:

$$F_i(\lambda',\lambda'')\in Q_F,\quad i=\overline{1,g}.$$

It should be noted that the domain $Q_F$ can be either single-connected or multi-connected, as shown in references [3].

The vector-functional $E_c$ is associated with the strategy $F(\lambda',\lambda'')$ through the mapping $\hat{R}$. In this case, the mathematical model of the efficiency evaluation problem is as follows:

$$E_c=[F(\lambda',\lambda'')]=\sup_{F(\lambda',\lambda'')\in Q_F}\hat{R}[F(\lambda',\lambda'')].\tag{2}$$

In a number of practical cases, the vector of uncontrollable variables $\lambda''$ is a random variable. Then model (2) takes the form:

$$E_c=[F(\lambda',\lambda'')]=\sup_{F\in Q_F}M''_{\lambda}\{\hat{R}[F(\lambda',\lambda'')]\}.\tag{3}$$

under the probabilistic constraints $P\{g_i(\lambda'')\le b_i\}$, $i=\overline{1,g}$.

It is clear that the system will be effective if it most fully satisfies the set of criteria. Then we can write:

$$\max_{F(\lambda',\lambda'')\in Q_F}\hat{R}[F(\lambda',\lambda'')] =\{\hat{R}_1[F(\lambda',\lambda'')],\ldots,\hat{R}_g[F(\lambda',\lambda'')]\}.\tag{4}$$

$$Q_F=\{F(\lambda',\lambda'')Ig_i[F(\lambda',\lambda'')]\le 0,j =\overline{1,m},F(\lambda',\lambda'')\in E^r\},\tag{5}$$

where $g_i(\ldots)$ is the constraint function of the *j*th indicator $F(\lambda',\lambda'')$; $E^r$ is an *r*-dimensional Euclidean space.

In equation (4), $F_i(x)$ represents the maximized values or their mathematical expectations if the maximized values themselves depend on the random parameters $\lambda''$. The essential feature of the problem (4), (5) is that the components of the target vector $R\left[F\left(\lambda',\lambda''\right)\right]$ are measured in different physical quantities, and their maximum values are achieved at the coincident points $F^i\left(\lambda',\lambda''\right)\in Q_F$, $i=\overline{1,g}$. The usual approach to solving it with convex objective functions $R_i\left(\lambda',\lambda''\right)$ and an admissible domain $Q_F$ is to replace the original problem (4), (5) with a parameterized one:

$$\max_{F(\lambda',\lambda'')\in Q_F}\hat{R}[\alpha,F(\lambda',\lambda'')]$$
$$=\sum_{i=1}^{g}\alpha_i\hat{R}_i[F(\lambda',\lambda'')],\ \alpha_i\geq 0,\ \sum_{i=1}^{g}\alpha_i=1. \quad (6)$$

Solving problem (6) for a set of parameters $\left(\alpha_i,\ldots,\alpha_g\right)^T$, we obtain a set of Pareto (effective) solutions $\Pi_F$.

$$\Pi_F=\left\{F_0\left(\lambda',\lambda''\right)|F_0\left(\lambda',\lambda''\right)\in Q_F,F\left(\lambda',\lambda''\right)\in Q_F,\right.$$
$$\left.\hat{R}_i\left[F\left(\lambda',\lambda''\right)\right]\geq\hat{R}_i\left[F_0\left(\lambda',\lambda''\right)\right]\right.$$

or

$$\hat{R}\left[\alpha,F\left(\lambda',\lambda''\right)\right]=\hat{R}\left[\alpha,F_0\left(\lambda',\lambda''\right)\right].$$

An alternative $F_0\left(\lambda',\lambda''\right)\in Q_F$ is Pareto-optimal if there is no alternative $H\left(\lambda',\lambda''\right)\in Q_F$ that satisfies each criterion at least as well as $F_0\left(\lambda',\lambda''\right)$ and that is strictly better than $F_0\left(\lambda',\lambda''\right)$ with respect to at least one criterion.

If $Q_F$ is convex and $\hat{R}_i$ is a real function defined on $Q_F$, then $\hat{R}_i$ is a quasi-concave function provided that the sets:

$$\left\{F_0\left(\lambda',\lambda''\right)|\hat{R}_i[F\left(\lambda',\lambda''\right)]\geq\beta\right\}$$

is convex for every real number.

Accordingly, $R_i$ is quasi-concave if:

$$\hat{R}_i[\alpha\cdot F_1\left(\lambda',\lambda''\right)+(1-\alpha)\cdot F_2\left(\lambda',\lambda''\right)]\geq$$
$$\min\left\{\hat{R}_i[F_1(\lambda',\lambda'')],\hat{R}_i[F_2(\lambda',\lambda'')]\right\}. \quad (7)$$

always when $F_1\left(\lambda',\lambda''\right)$, $F_2\left(\lambda',\lambda''\right)\in Q_F$ and $0\leq\alpha\leq 1$. A function $\hat{R}_i\left[F\left(\lambda',\lambda''\right)\right]$ is strictly quasi-concave if:

$$\hat{R}_i[\alpha\cdot F_1\left(\lambda',\lambda''\right)+(1-\alpha)\cdot F_2\left(\lambda',\lambda''\right)]>$$
$$\min\left\{\hat{R}_i[F_1(\lambda',\lambda'')],\hat{R}_i[F_2(\lambda',\lambda'')]\right\}. \quad (8)$$

The resulting finite set of points from the $\Pi_F$ domain in accordance with (7) is presented to the expert, who selects one that is preferred over the others.

If conditions (6), (8) are not met, then it is advisable to analyze only inefficient solutions that are located in the zone of global extrema of the maximized functions.

The process of solving problem (6) can be represented geometrically as a movement in the space of hyperplane criteria:

$$G=\sum_{i=1}^{g}\alpha_i\hat{R}_i[F(\lambda',\lambda'')], \quad (9)$$

in the direction inverse to the parameter vector $\left(\alpha_1,\ldots,\alpha_g\right)^E$. The maximum is achieved when the hyperplane $G$ becomes tangent to the valid region of the objective function values Φ. The domain of objective values:

$$\Phi=\left\{\hat{R}_i\left[F(\lambda',\lambda'')\right]|F(\lambda',\lambda'')\in Q_F\right\}$$

represents the mapping of the set $Q_F$ in the criterion space. To calculate the required number of effective points, it is necessary to find the global extremum of expression (6) for each set of parameters $\left(\alpha_1,\ldots,\alpha_g\right)^E$.

The Pareto principle does not single out a single solution $E_c\left[F\left(\lambda',\lambda''\right)\right]$, it only narrows the set of alternatives $F\left(\lambda',\lambda''\right)$. The construction of the set (6) facilitates the procedure for selecting UAV indicators, takes into account their impact on system efficiency, and reduces the set of initial options.

Another approach to solving problem (1) or (2) is to form the resulting quality indicator in order to ensure the comparability of system options. One of the options for such formation is a linear reconciliation of indicators, i.e., instead of g different indicators, one resulting indicator of the form is formed:

$$\Xi[F(\lambda',\lambda'')]=\sum_{i=1}^{g}\alpha_i\hat{R}_i[F(\lambda',\lambda'')], \quad (10)$$

where $\alpha_i$ is a positive number, and in the case of dimensionless quantities:

$$\hat{R}_i\left[F(\lambda',\lambda'')\right]\sum_{i=1}^{g}\alpha_i=1.$$

This method of convolution is equivalent to ranking indicators, since the value of $\alpha_i$ shows how much the objective function $\Xi$ changes when the indicator with the number i changes by one:

$$\alpha_i = \frac{\delta \Xi}{\delta \hat{R}_i}, \quad i = \overline{1, g}. \tag{11}$$

One of the problems in measuring UAS efficiency is to take into account the level of flight safety as one of the components of (1). In this case, two fundamentally different approaches are possible. The first one is to convert the level of flight safety into cost indicators, which is known to be a highly complex task burdened by the moral aspect and social consequences. Another approach is based on the conversion of flight safety indicators into the category of restrictions. The restriction is based on a guaranteed level. The complexity of measuring performance in this way is determined by the possibility of obtaining guaranteed estimates. The meaning of the guaranteed result principle is as follows.

Since for any $F(\lambda', \lambda'')\hat{R}[F(\lambda', \lambda'')] \le$ $\le \max\limits_{F(\lambda', \lambda'')} \hat{R}[F(\lambda', \lambda'')]$, then for $\lambda''$.

$$\hat{R}^*[F(\lambda', \lambda'')] = \max_{F(\lambda', \lambda'')} \min_{\lambda'' \in Q_\lambda} \hat{R}[F(\lambda', \lambda'')] \le \max_{F(\lambda', \lambda'')} \hat{R}[F(\lambda', \lambda'')]. \tag{12}$$

Here, $\hat{R}^*[F(\lambda', \lambda'')]$ is called a guaranteed estimate (guaranteed strategy) in the sense that $\exists(\lambda'')$ guarantees a choice $F(\lambda', \lambda'') = F^*(\lambda', \lambda'')$ such that the value of the objective function is not less than $\hat{R}^*$. A guaranteeing strategy can be obtained by solving optimization problems of the form:

*a)* $\min\limits_{\lambda'' \in Q_\lambda} \hat{R}[F(\lambda', \lambda'')] \forall F(\lambda', \lambda'')$, which leads to the estimates $\lambda'' = \tilde{\lambda}''$, and $\hat{R}^*[F(\lambda', \lambda'')] =$ $= \hat{R}[F(\lambda', \lambda'')]$.

*b)* $\max \hat{R}[F(\lambda', \lambda'')]$ and as a result, we obtain:

$$F(\lambda', \lambda'') = F(\lambda', \tilde{\lambda}'') \text{ and } \hat{R}^*[F(\lambda', \lambda'')].$$

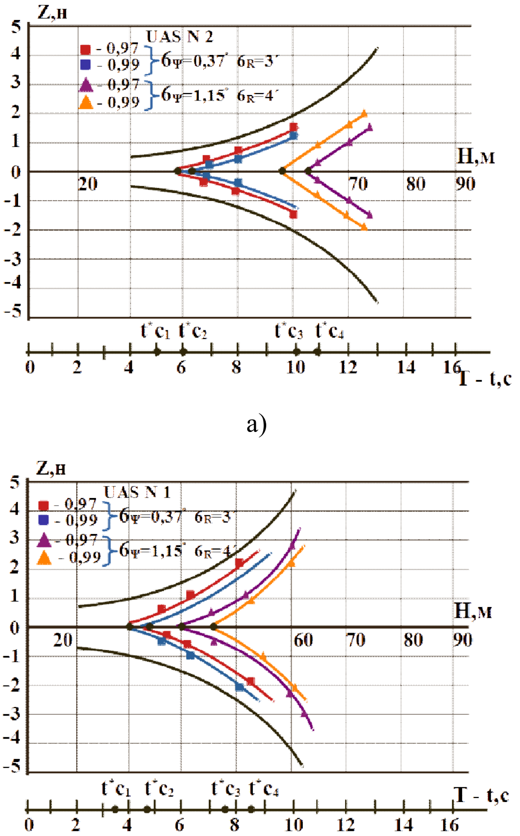
The guaranteed estimate can be significantly improved if the values of the parameter $\lambda''$ are known in advance. Thus, the problem of evaluating the UAS efficiency taking into account the guaranteed level of flight safety, taking into account (1), (3), (12), takes the form

$$E_c[F(\lambda', \lambda'')] = \left\{ \max_{F(\lambda', \lambda'') \in Q_F} M''_\lambda \left\{ \hat{R}_i [F(\lambda', \lambda'')], \right\} \right. \quad i = 1, \ldots, 1 - i \Big\}, \tag{13}$$

$$\max_{F(\lambda', \lambda'')} \min_{\lambda'' \in Q_\lambda} R_1 [F(\lambda', \lambda'')] \le \max_{F(\lambda', \lambda'')} R_1 [F(\lambda', \lambda'')], \tag{14}$$

$$P\{g_j(\lambda'') \le b_j\}, \quad j = \overline{1, g}. \tag{15}$$

Solving problems (13) – (15) allows us to estimate the real efficiency, taking into account the operating conditions of the UAS. As an example, Fig. 3 for the parameters of the model (14), (15) show changes in the current and reflexive resources of the UAS action depending on the parameters of the control and controlled subsystems and the moment of time ($T = t_k - t_0$). Comparison of these results shows that for both variants of navigation systems, the transition to a slower speed aircraft reduced the landing system (LS) limit by about 1.5 times. For each of the aircraft types, the use of a more accurate navigation system can reduce the range by about 2 times. With increasing requirements for the quality of decisions made, the limit of the SP operation increases, as illustrated by the effect of the level of $\beta_1$ (0.97 and 0.99) on the size of $L_1(t, \beta_1)$.



a)

b)

Fig. 3. Changes in the current (a) and reflexive (b) resources of UAS action depending on the parameters of the control and controlled subsystems and the time ($T = t_k - t_0$) of the landing mode

## IV. TYPES OF LINKS BETWEEN DRONE PERFORMANCE AND SYSTEM PERFORMANCE

Depending on the conditions of use of UAS, an implicit or explicit relationship can be established between their performance and the performance of the system under service. Replacing one vehicle with another that has higher quality indicators does not always lead to a gain in terms of improving higher-order system parameters. For example, ensuring a potential increase in the capacity of zones, regularity and efficiency of flights by improving the quality of radar, communication, and radio navigation support is not always realized under normal operating conditions. Nevertheless, the effect can be obtained in special (extreme) situations, especially in terms of improving flight safe. Thus, when solving the problems of evaluating the effectiveness of the first type with implicit system linkages, as mentioned above, it is necessary to bring the compared options into a comparable form in terms of $F(\lambda', \lambda'')$ or functional tasks. Such a conversion is based on the use of additional information about the types of system links and operating conditions. In this case, a step-by-step multi-step decision-making procedure is performed, which is characterized by a transformation string:

$$\left\{\Phi\left[F(\lambda', \lambda'')\right],\ I(F, \lambda', \lambda'', y)\right\}, \tag{16}$$

where $I(F, \lambda', \lambda'', y)$ is additional information about the system and the conditions of functioning of $y$.

Thus, for example, with implicit system links, applying informal procedures at the first stage and transformations of the type (16), in particular (10), at the following stages it is possible to formulate the resulting quality indicator b of the applied UAS. This indicator can be used to adjust the given costs for the production of a unit of the basic system, the associated capital investment and operating costs for the basic variant.

In the case of explicit systemic links, a transformation of the type (16) is used to assess the impact of quality indicators $F(\lambda', \lambda'')$ on the components of efficiency (1).

The magnitude of the effect is estimated using this approach when the components are expressed as a function of many variables:

- performance $P\left[F(\lambda', \lambda'')\right]$,
- operating costs $EB\left[F(\lambda', \lambda'')\right]$,
- present value costs $PB\left[F(\lambda', \lambda'')\right]$.

Despite the difference between the forms of expression of the economic effect, the methods of their calculation are identical. The national economic and self-supporting forms of the effect are defined in the same way, as the difference between the results and the costs of achieving them. In other words, the economic effect is a difference indicator. This indicator can be presented in one of the following forms:

$$\begin{aligned} &\max_j \varepsilon^j, \\ &\max_j \left(P_T^j - \varepsilon_T^j\right), \\ &\max_j \left(\textstyle\sum_{t=t_n}^{t_k} P_T^j\right) \cdot \alpha_t \textstyle\sum_{t=t_n}^{t_k} \varepsilon_T^j \cdot \alpha_t, \\ &\max_j \textstyle\sum_{t=t_n}^{t=t_k} \left(P_T^j - \varepsilon_T^j\right) \cdot \left(1 + E_H\right)^{t_p - t}, \end{aligned} \tag{17}$$

where $P_T^j, P_t^j, \varepsilon_T^j, \varepsilon_t^j$ are, respectively, the total results and costs for the entire period of the measure implementation in the *t*th year; $\alpha_t = \left(1 + E_H\right)^{t_p - t}$ is the coefficient of bringing the results and costs of the *t*th year to one point in time (the calculation year $t_p$); $E_H = 0.1$ is the standard capital investment efficiency ratio; $t_H$, $t_k$ are the initial year (the year of the start of financing of works related to the measure implementation) and the final year of the calculation period, respectively; $j$ is the index of the option under consideration.

One of the cases of implementing a measure is when the choice must be made among options that differ only in the dynamics and magnitude of the cost components (one-time and recurrent). In this case, the economic criterion of maximum effect (17) is transformed into another, simpler one – minimum total costs:

$$\max_j \textstyle\sum_{t=t_n}^{t_k} \varepsilon_T^j \cdot (1 + E_H)^{t_p - t} \cdot \max_j \varepsilon_T^j. \tag{18}$$

However, the absence of a change in the results does not eliminate the need to evaluate these results in cost terms. This is because the reduction in costs in the production of final products using the new technique compared to the use of the basic technique is not a reason to use the new technique if the products are ultimately unprofitable.

In this regard, and for measures of the type under consideration, the economic effect is calculated using the formula:

$$\varepsilon_T = \textstyle\sum_{t=t_n}^{t_k} (P_t - \varepsilon_t) \cdot (1 + E_H)^{t_p - t}. \tag{19}$$

The fundamental point of this methodology is the need for a cost estimate of the production, social, economic and other results achieved, even if they are identical in the compared options.

The complexity of assessing the economic effect of the UAS system lies in the lack of methods for calculating components (4) – (6) and the need to take into account the component characterizing the level of flight safety $Q$.

If the probability distribution of the components of the state vector $F\{Z_1, Z_2, \ldots, Z_n, \tau\}$ is known, provided that the boundary has never been violated until $t+\tau$. The density of this probability is usually defined as the solution of the second Kolmogorov equation. Let us denote by $Q$ some safety criterion. Then $Q$ can be represented as follows:

$$Q = \int_{\Omega(\tau)} f\left(\vec{Z}\right) / df\left(\vec{Z},\tau\right). \qquad (20)$$

Here, $f\left(\vec{Z}\right)$ is a weighting function that determines the content of the criterion $Q$; $\Omega(\tau)$ is the region of permissible values of the vector $\vec{Z}$. As can be seen from (20), to quantify the level of flight safety, it is necessary to know or be able to construct the region $\Omega(\tau)$. For obvious reasons, this criterion should be transferred to the category of restrictions that are unacceptable for violation.

It is obvious that, when calculating $\varepsilon_T$, it is necessary to take into account the savings due to the reduction of non-productive costs associated with aircraft waste to the alternate airfield, erroneous change of echelons, unnecessary waste to the second circle; take into account the savings to reduce the consumption of fuels and lubricants as a result of streamlining the flow of aircraft and optimizing flight paths, reducing non-productive maneuvers of aircraft, etc.

To solve problems (4) – (6), a formalized linkage of unmanned system parameters with cost indicators is required. This problem has not been solved until recently and requires an assessment of the functional effect.

The functional effect is manifested in the influence of the characteristics of the means of a complex system on the indicators of its functioning.

In accordance with the considered formula (19), it is necessary to build an efficiency model in which the variables are expressed as $P_t\left[F\left(\lambda', \lambda''\right)\right]$, $PB_t\left[F\left(\lambda', \lambda''\right)\right]$, and $EB_t\left[F\left(\lambda', \lambda''\right)\right]$. It is obvious here that it is possible to evaluate the actual efficiency of the UAS and/or, at the next hierarchical level, the air navigation system (ANS) as a whole.

## V. CONCLUSIONS

Since cargo drones are used for urgent delivery of goods or their delivery to hard-to-reach areas while maintaining the required level of flight safety, it is important to measure performance with due regard to extreme situations that arise in the field. However, it should be borne in mind that such measurement can only be provided for specific types of systems, considering their specific functioning and structure. Another prerequisite is the presence of microsystem links between the UAS under study as an object and a higher-order system, such as an air navigation service system. The basis of the efficiency model for this case is the model of the functional effect, i.e., the effect that results from the functioning of a UAS with a $g$-dimensional quality vector function, considering the multiconnected domain of constraints of the unmanned system.

## VI. REFERENCES

[1] R. E. Edwards, *Functional Analisis. Theory and Applications*. New York, Toronto, London, 1965, 1072 p.

[2] Volodymyr Kharchenko, “The Use of Unmanned Aircraft Systems for Fast Delivery Goods,” *Logistics and Transport*, no. 3–4(47–48), 2020. Wroclaw pp. 89–101. ISSN 1734-2015.

[3] H. Li and V. Kharchenko, “Methods for Measuring the Efficiency of UAVs in the Air Navigation System,” *Electronics and Control Systems*, vol. 1(79), pp. 78–83, 2024. https://doi.org/10.18372/1990-5548.79.18445.

[4] Chang Deng, Wenjun Xu, Chia-Han Lee, Hui Gao, Wenbo Xu, and Zhiyong Feng, "Energy Efficient UAV-enabled Multicast Systems: Joint Grouping and Trajectory Optimization," GLOBECOM 2019 – 2019 IEEE Global Communications Conference, IEEE, 2019.

[5] Markus Lieret, et al., "Automated in-house transportation of small load carriers with autonomous unmanned aerial vehicles," *2019 IEEE 15th International Conference on Automation Science and Engineering (CASE)*, IEEE, 2019.

[6] Yujing Chen, et al. "Optimal Trajectory Design for Unmanned Aerial Vehicle Cargo Pickup and Delivery System based on Radio Map," *IEEE Transactions on Vehicular Technology*, 2024.

[7] Kakuya Iwata, and Osamu Matsumoto, "Aerial Cargo Robot (Cargo UAV)," *Journal of Robotics and Mechatronics*, 26.3, 394–395, 2014.

[8] Niamat Ullah Ibne Hossain, Nazmus Sakib, and Kannan Govindan, "Assessing the performance of unmanned aerial vehicle for logistics and transportation leveraging the Bayesian network

approach," *Expert Systems with Applications*, 209, 118301, 2022.

[9] J. J. Castillo-Zamora, J. Escareno, I. Boussaada, O. Labbani, & K. Camarillo, “Modeling and control of an aerial multi-cargo system: Robust acquiring and transport operations,” in *2019 18th European Control Conference (ECC)*, 2019, pp. 1708–1713. IEEE.

[10] Matko Orsag, et al., "Dexterous aerial robots–mobile manipulation using unmanned aerial systems," *IEEE Transactions on Robotics*, 33.6, 2017, 1453–1466.

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**Хаоян Лі, В. П. Харченко. Концептуальний аспект вимірювання ефективності безпілотної авіаційної системи**

У статті досліджено концептуальні аспекти вимірювання ефективності безпілотних систем, включаючи розробку підходу до вимірювання ефективності безпілотних літальних апаратів. Під ефективністю вантажних безпілотних літальних апаратів розуміється здатність цих апаратів виконувати свої завдання вчасно та економічно ефективно, з максимальним використанням та мінімізацією втрат ресурсів, зберігаючи при цьому прийнятний рівень безпеки польотів. У зв’язку із цим необхідно підкреслити, що ефективність вантажних безпілотних літальних апаратів є багатогранною, включаючи технічні, експлуатаційні, економічні, екологічні та регуляторні аспекти. Постійний прогрес у цих сферах допомагає впроваджувати і оптимізувати вантажні дрони для різноманітних застосувань – від доставки «останньої милі» до ланцюгів постачання у віддалених районах. У статті описано два способи вимірювання ефективності вантажних дронів.

**Ключові слова:** ефективність; вантажний безпілотний літальний апарат; безпілотна авіаційна система; інтегральна ефективність; вектори керованих і некерованих змінних; рефлексивний ресурс дії UAS; моделі з явними та неявними зв’язками параметрів системи.

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