DEA-methodology for criterial evaluation of configurations of spacecraft for earth remote sensing

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Abstract. The modern pace of life is inexorably increasing, which requires the creation of more and more advanced devices in a short time. One of the high-tech industries that provide socio-cultural needs is aerospace. Modern spacecraft are complex systems for the design of which requires a large amount of resources. Existing automated design systems are not able to provide design support at the pre-competitive (external) design stage. The purpose of the system is to create a decision-making support tool for designing complex systems of automated spacecraft for earth remote sensing. The use of the information system will create conditions for increasing the competitiveness of the manufacturer and will bring the design of aerospace equipment to a higher quality level.

Keywords. information system structure, automatic spacecraft, Earth remote sensing, operation algorithm, configuration selection methods.

Introduction

The level of technology is rapidly developing due to the increasing demands of society. The pace of modern man sets new rules for receiving and processing relevant information in any area. Timely and accurate knowledge gives the opportunity to make the right decisions and get the greatest benefit in the future.

The use of automated spacecraft is becoming increasingly widespread as a means of obtaining the most timely information. Automated spacecraft for earth remote sensing (ERS) is a convenient means of monitoring the earth's surface and near-earth space. However, they represent a very complex system consisting of many subsystems, the interconnection of which is described by many laws. Given this fact, the design of space technology is a challenge.

Design and creation of aerospace equipment is carried out in strict accordance with the established regulatory documentation. This is shown in Figure 1. All stages of the life cycle obey the rules, but despite this, the stage of pre-competitive (external) design has no strict settings. This state of affairs is associated with the complexity of formalization of works on conceptual design of automated spacecraft for ERS.
Not only the question of the logic and technology of computer-aided design of automated spacecraft is insufficiently investigated, but also there are no theoretical works related to the choice of parameters and logic of the design process at the stage of pre-sketch design. At the same time, this preliminary stage for the developer that is the key one, since it is there that he analyzes his capabilities and considers the options for solving the tasks set by the customer [1].

In this regard, the creation of a preliminary configuration analysis system is a current issue. The use of an information system in the preliminary development of a product will reduce the time for developing future automated spacecraft for ERS concepts and increase the chances of receiving an order for a manufacturing company which main goal is to make a profit.

The main purpose of the research is to create a decision support system (DSS) for design engineers, which will allow specialists with a certain level of knowledge to form a rational configuration of the spacecraft during the pre-sketch works. The DSS system can increase the quality of project development, as it is able to interact with a person and offer the most rational solutions to current problems from a variety of possible [2].

**Method for optimization of design solutions DEA (Data Envelopment Analysis)**

The Data Envelopment Analysis (DEA) method is widely used to assess the comparative effectiveness of various complex production regional systems. The method is used to analyze organizations, processes, production and operations in various fields of activity: insurance, banking, oil and gas, retail, services, health care, education and others.

The basic model of the DEA methodology was developed in 1957 by the American researcher Farrel M.J. [4] and improved in 1978 by Charnes, Cooper, Rhodes [5]. Subsequently, in 1984, this approach was developed by Banker, Charnes, Cooper [6].

When solving problems by the DEA method, it is assumed that a complex system has a set of \( m \) input characteristics and \( n \) output parameters. This is represented in Figure 2.
Output values $Y_1, Y_2, \ldots, Y_n$ are taken in such a way that each of them characterizes the target property of the system. Thus, with an increase in output values, the age will be the integral indicator of the efficiency $f$ of the complex system. In the mathematical formulation, this can be represented by the formula (1) as a partial derivative of the performance indicator for the chosen parameter.

$$
\frac{\partial f(Y_1, Y_2, \ldots, Y_n)}{\partial Y_i} > 0, \quad i = 1, n
$$

Input value $X_1, X_2, \ldots, X_m$ are the characteristics by which the total efficiency ratio is managed. They must be chosen in such a way that a decrease in the values of input characteristics leads to an increase in the value of the efficiency index. In the mathematical formulation, this is reflected by formula (2).

$$
\frac{\partial f(X_1, X_2, \ldots, X_m)}{\partial X_i} < 0, \quad i = 1, m
$$

Based on the choice, which contains all the necessary variables for a complete analysis of the system from the point of view of the designer, a function of assessing the quality of a complex system is compiled. The function has the form represented by the formula (3).

$$
f = \frac{Y_1 \cdot u_1 + Y_2 \cdot u_2 + \cdots + Y_n \cdot u_n}{X_1 \cdot v_1 + X_2 \cdot v_2 + \cdots + X_m \cdot v_m}
$$

In formula (3), the quantities $u_i$ (i = 1, 2, ..., n) and $v_i$ (i = 1, 2, ..., m) are weighting factors that take a positive value for various system configurations. In the main methodology, they require only positive values and are arbitrary [7].

When forming the expression for the complex performance indicator, it is necessary to normalize the input characteristics and output parameters in the interval [0; 1]. This will allow not to introduce the coefficient of magnitude of the values and to simplify the software implementation of the information system. However, the main advantage of the DEA method is that it allows to evaluate the efficiency of the system not by any single selected criterion or artificially created coefficient, but by all factors affecting the system as a whole. In addition, this method allows not only to assess the efficiency of the system [8], but also clearly see what input characteristics affect the value of the quality assessment function to the greatest extent.

**Decomposition and analysis of the automated spacecraft for earth remote sensing for determination the input characteristics and output parameters**

Automated spacecraft for ERS in the visible and near infrared spectrum have a similar system structure [8].
The initial division of systems occurs according to the principle of belonging to the service platform and the target load. On this basis, there are service systems that ensure the functioning of the spacecraft during operation, and payload systems that allow to perform target tasks.\[9\-10\]

Each large group consists of the subsystems shown in Figure 3, which are responsible for specific tasks. For their implementation, it is necessary to take into account both specific input and output data (Figure 3), which are largely dependent on the apparatus goal.\[11\]

We will analyze the characteristics and parameters of the systems and the entire apparatus, following the hierarchical structure of the product. On the basis of expert estimates, it was revealed that the automated spacecraft for ERS should have the most important output parameters for optimization such as "cost", "volume of the hull", "lifetime", "linear / angular resolution on the ground". Input characteristics are the data that are the output parameters of the subsystems of the device.

Considered input data are:
- for the optoelectronic surveillance subsystem - cost, length of the optical system, maximum diametrical size of the optical system;
- for high-speed radio link subsystem - cost, number of antennas on the device, data transfer rate;
- for the subsystem of the onboard control system - cost, energy consumption, the volume of mathematical models;
- for the subsystem of energy supply - cost, area of solar panels, capacity batteries;
- for the subsystem providing thermal conditions - cost, area of the heaters, length of the axial pipeline;
- for service communication channel subsystem - cost, power consumption, number of transmitting and receiving devices;
- for the subsystem of the propulsion system - the cost, the number of engines, the consumption of the working fluid;
- for the frame - length, height, width.

For finding integrated indicator of automated spacecraft for ERS efficiency need to allocate the output parameters for the subsystems. Following parameters were selected:

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**Figure 3** Structure of automated spacecraft for ERS

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\[\text{Considered input data are:}\]
\[\text{• for the optoelectronic surveillance subsystem - cost, length of the optical system, maximum diametrical size of the optical system;}\]
\[\text{• for high-speed radio link subsystem - cost, number of antennas on the device, data transfer rate;}\]
\[\text{• for the subsystem of the onboard control system - cost, energy consumption, the volume of mathematical models;}\]
\[\text{• for the subsystem of energy supply - cost, area of solar panels, capacity batteries;}\]
\[\text{• for the subsystem providing thermal conditions - cost, area of the heaters, length of the axial pipeline;}\]
\[\text{• for service communication channel subsystem - cost, power consumption, number of transmitting and receiving devices;}\]
\[\text{• for the subsystem of the propulsion system - the cost, the number of engines, the consumption of the working fluid;}\]
\[\text{• for the frame - length, height, width.}\]
• for the subsystem of optoelectronic surveillance - linear (angular) resolution on the ground;
• for high-speed radio link subsystem - the volume of data transmitted to the ground station;
• for the subsystem of onboard control system - the number of control channels;
• for power supply subsystem - generated power;
• for the subsystem providing the thermal regime - the time of stabilization of the thermal regime;
• for the subsystem of the service communication channel – noise/useful signal ratio;
• for the subsystem of the propulsion system - thrust (impulse);
• for the frame – volume.

These parameters are the input characteristics for evaluating the complex efficiency of the device. They provide a comprehensive assessment of all systems, allowing a comprehensive study of the configuration of the future product.

The following indicators were taken as output parameters for the evaluation of the entire apparatus:
• cost of development and production of one sample;
• lifetime of the automated spacecraft for ERS;
• project implementation period.

The above characteristics are identified on the basis of expert estimates of specialists. Their structure can be specified at further development of the system and adjusted under additional conditions of a new product design.

Mathematical model of comparative evaluation of automated spacecraft for ERS subsystems

As a tool for comparative evaluation and optimization of characteristics, the method of linear programming Data Envelopment Analysis (DEA) is adopted. The choice of this method for a comprehensive assessment of the effectiveness of the automated spacecraft for ERS is based on its indifference to the nature of the input characteristics and output parameters. This is an important aspect in the formation of the initial configuration of existence [1] at the pre-competitive design stage.

For the formation of the initial composition of the automated spacecraft for ERS, the developer, as a rule, uses the accumulated experience. The choice of equipment is carried out arbitrarily without taking into account the exact characteristics of a particular equipment. Also, the clarification of the data on the components takes a lot of time. [12]

The decision support system, based on the DEA method, will be able to assess the effectiveness of the subsystems and the whole automated spacecraft for ERS according to the stated task.

For correct comparison of the results, it is necessary to strictly set the weight coefficients. This can be done in two ways:
1. Automatic assignment of the weighting factors of IS through the calculation of all possible configurations of subsystems selected and "frozen" values of the weight coefficients, the comparison coefficients of efficiency, selection of the largest and ranking by its value of all options on the interval [0;1];
2. expert estimates of input characteristics and output parameters to establish their weights when solving a problem.

In this work, it is proposed to use the second option of assigning weights, as it most fully meets the requirements for creating DSS systems.

For example, consider the mathematical formulation for the subsystem of optoelectronic observation [9].

The goal is to obtain the highest quality images of the earth's surface and near-earth space in the visible spectrum. This can be achieved with the system of optoelectronic surveillance with the characteristic of high resolution on the ground. First, the design limitation is the cost of the developed unit. Second, its diametrical size. Third, the length of the optoelectronic surveillance system.[13]

From the above it follows that the weight coefficient for the input characteristic "cost" will be assigned the highest value. For "diametrical sizes" - the average value of the weight coefficient, and for "system length" - the smallest value.
Let us compile the expression to find the measure of the effectiveness of integrated subsystems optoelectronic surveillance. It is represented by a set \((4)\). To best meet the conditions of the problem, the function must have a minimum value, which is explained by the best detail of the image.

\[
\begin{align*}
& f_1^\text{cohn} = \frac{Y_{\text{rest}}^1 \cdot u_{\text{rest}}^1}{X_p^1 \cdot v_p^1 + X_{\text{diam}}^1 \cdot v_{\text{diam}}^1 + X_{\text{ln}}^1 \cdot v_{\text{ln}}^1} = 1,4; \\
& f_2^\text{cohn} = \frac{Y_{\text{rest}}^2 \cdot u_{\text{rest}}^2}{X_p^2 \cdot v_p^2 + X_{\text{diam}}^2 \cdot v_{\text{diam}}^2 + X_{\text{ln}}^2 \cdot v_{\text{ln}}^2} = 0,97; \\
& f_3^\text{cohn} = \frac{Y_{\text{rest}}^3 \cdot u_{\text{rest}}^3}{X_p^3 \cdot v_p^3 + X_{\text{diam}}^3 \cdot v_{\text{diam}}^3 + X_{\text{ln}}^3 \cdot v_{\text{ln}}^3} = 0,67.
\end{align*}
\]

Where \(Y_{\text{rest}}^k\) - the magnitude of the characteristic of linear resolution on the ground automated spacecraft for ERS; \(u_{\text{rest}}^k\) - weight coefficient of linear resolution; \(X_p^k\) - the value of the optoelectronic system; \(X_{\text{diam}}^k\) - the magnitude of the characteristics of the diametrical dimensions; \(X_{\text{ln}}^k\) - the value of the characteristics length of the system; \(v_p^k, v_{\text{diam}}^k, v_{\text{ln}}^k\) - the weighting characteristics of the prices of diametrical sizes and lengths of the system, respectively. The values of the obtained parameters should be normalized on the interval \([0;1]\) for their use in further calculations. Thus, \(f_1^\text{cohn} = 1; f_2^\text{cohn} = 0,7; f_3^\text{cohn} = 0,5.\)

From the obtained expressions, it is obvious that the third configuration is the most preferable.

Other subsystems of the automated spacecraft for ERS are considered similarly.

Further, we compile a summary table 1, which includes the values of the coefficients of complex efficiency for each subsystem of the automated spacecraft for ERS.[14-19]

**Table 1.** Values of the integrated performance indicator for the subsystems of the automated spacecraft for ERS

| Subsystems of the automated spacecraft for ERS | Coefficient of complex efficiency | Normalized coefficient of complex efficiency |
|---------------------------------------------|----------------------------------|---------------------------------------------|
| Optoelectronic surveillance system          | 1.4                              | 1                                           |
|                                           | 0.97                             | 0.72                                        |
|                                           | 0.67                             | 0.53                                        |
| High Speed Radio System                    | 1.25                             | 1                                           |
|                                           | 1.03                             | 0.83                                        |
|                                           | 0.80                             | 0.64                                        |
| Onboard control complex                    | 1.14                             | 1                                           |
|                                           | 0.96                             | 0.84                                        |
|                                           | 0.72                             | 0.63                                        |
| Power supply system                        | 1.17                             | 1                                           |
|                                           | 0.95                             | 0.81                                        |
|                                           | 0.87                             | 0.74                                        |
| Thermal Management System                  | 1.22                             | 1                                           |
|                                           | 0.93                             | 0.76                                        |
|                                           | 0.79                             | 0.65                                        |
| Service communication channel system       | 1.09                             | 1                                           |
|                                           | 0.82                             | 0.75                                        |
|                                           | 0.69                             | 0.63                                        |
| Propulsion system                          | 1.33                             | 1                                           |
|                                           | 0.99                             | 0.74                                        |
|                                           | 0.73                             | 0.55                                        |
| Frame                                      | 1.29                             | 1                                           |
|                                           | 0.91                             | 0.71                                        |
|                                           | 0.81                             | 0.63                                        |

The obtained values will be applied when calculating the coefficient of the complex indicator for the final designed product.
Mathematical model of comparative evaluation of the automated spacecraft for ERS configurations

To optimize the parameters of the automated spacecraft for ERS configuration, the above method of determining the complex efficiency index is used. Optimized output parameters of subsystems are used as input characteristics. Integral performance indicator for the entire device to determine the most advantageous configuration under the specified operating conditions.

The function of determining the complex performance indicator is defined by the expression (5).

\[
 f_i = \frac{Y_{\text{design}} \cdot u_{\text{design}} + Y_{\text{opr}} \cdot u_{\text{opr}} + Y_{\text{realiz}} \cdot u_{\text{realiz}}}{X_{oess} \cdot v_{oess} + X_{hsrs} \cdot v_{hsrs} + X_{occ} \cdot v_{occ} + X_{ps} \cdot v_{ps} + X_{tms} \cdot v_{tms}} \cdot \frac{1}{X_{scs} \cdot v_{scs} + X_{ps} \cdot v_{ps} + X_{frame} \cdot v_{frame}}
\]

where \( i = 1, k \); \( k \) - the number of possible variants of the automated spacecraft for ERS configuration of the subsystem variations.

The weights of the characteristics and parameters when calculating the efficiency coefficient are assigned automatically when carrying out optimization. Such an approach is possible when implementing the classical theory of the DEA method. After performing the calculations, the IS provides an optimized version of the configuration of the automated spacecraft for ERS for the specified operating conditions.

**Conclusion**

The use of the DEA-method for determining the optimal configuration of the automated spacecraft for ERS is appropriate because of its indifference to the nature of the input characteristics and output parameters, which is necessary given the conflicting requirements at the initial design stage of the automated spacecraft for ERS. The applicability of the method in management systems also makes it possible to use it in the development of technical systems, as the most formalized in comparison with the social ones.

Further studies of the application of DEA-methodology in the field of designing complex technical systems will allow you to create intelligent decision support systems. Its use will ensure a reduction in the development time of the project at the pre-competitive stage and will create advantages for users over competitors.

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