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Methodology for criteria analysis of multivariant system

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ABSTRACT

Introduction. Trends in the development and application of modern machine-building systems somehow create the problem of analysis and choice in the presence of alternative objects, or with a large number of comparison criteria - indicators of the effectiveness of objects or systems. The main difficulties in optimizing the solution for designing production systems depend on complex technological problems: a large number of influencing factors and the absence of patterns. The choice of effective objects and systems is often a complex and multi-criteria process that requires a lot of time and, as a result, reduces the efficiency of the organization of production preparation. In this regard, for the preparation and adoption of technical and economic decisions of various complexity in production conditions, a systematic approach is required using the most rational forms and methods of organizing production. **The purpose of the work:** to create a generalized methodology for the criteria analysis of multivariant systems. **The methods of investigation.** A methodology is proposed aimed at improving the efficiency of the organization of pre-production due to a reasonable choice from a large number of options. The choice of a rational solution option is based on the ranking of indicators by priority at the time of making a reasonable decision in a specific situation and the type of object and system under consideration. Indicators can be variable, taking into account the specifics of production. **Results and Discussion**. A comparative analysis of the process of edge cutting machining of the *STEF-1* fiber-glass polymer composite material with an interlocking side mill carrying various insert materials is conducted as an example of the practical application of the proposed methodology. As comparison parameters, the period of technological tool life, cutting performance and reduced costs in the implementation of cutting are taken. According to the results of a comparative multi-criteria analysis carried out according to the presented method, it follows that the priority in the system under consideration with the specified parameters for the implementation of the technology is the tool equipped with *WC–3Co* alloy inserts, which has the highest value of the weight criteria coefficient. According to the results of the analysis, a tool equipped with *WC–2TaC–6Co* alloy inserts is close in rationality, which allows recommending it as an analogue when choosing. The scope of the proposed application of the methodology is seen if it is necessary to analyze complex multivariant systems/objects. The objects/systems can be both variants of scientific solutions under various conditions of comparability, as well as design, technological solutions, structural and instrumental materials at the selection stage in the design and technological preparation of production, variants of the system implementation algorithm. The comparison parameters can be physical, mechanical, technological, operational properties; technical, economic and quality indicators; specific characteristics and parameters. The proposed technique will reduce the time for making new decisions under varying production conditions. The use of the methodology with known and well-defined parameters characterizing multivariant systems makes it possible to algorithmize, and subsequently automate, the process of organizational and technological preparation of production.

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Introduction

Development and application trends of modern machine-engineering systems in any case raise a question of analysis and selection in the presence of alternative facilities, or on condition of a large number of comparison criteria, namely the performance indicators of facilities or systems [1–10].

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Due to this, the preliminary stage of any industrial system is critical for any enterprise. The competitive abilities directly depend on approaches to the industrial operation process as a generalized production system having numerous target functions depending on various factors [11, 12]. The primary estimation of the production system performance should be made at the preparation stage for further long-term solutions, which in turn directly impact the amount of capital investments in whole. The basic challenges of the selection of the best design option for production systems depend on complex process tasks, meaning a large number of contributing factors and absence of patterns [13, 14].

Knowledge of design baseline allows selecting the most rational options to arrange the production system and develop management algorithms for further automation of preparation and design process of production systems using mathematical methods. When designing a production system it is necessary to have a database with information, comprising necessary data on the subject and representing the existing connections and/or patterns between the elements and properties of the compared facilities [15–21]. The availability of information on the analyzed facilities allows making informed decisions, which may be the basis for modeling, predicting and optimizing the system.

This is of particular relevance at the stage of organizational or process, when it is necessary to make an informed choice from a large number of options in a short time.

With this, one is targeted to output economical and processing production performance. The selection of effective facilities and systems is often a challenging and multi-criteria process requiring significant time expenditures, which results in the decrease of efficiency in process preparation [22–26]. In real settings, the signs are individually determined, according to which the assessment is made and the optimal solution is selected. Considering the fact that the parameters are targeted to achieve the extreme points (increase or decrease) and, while providing manufacturing flexibility, when ranking parameters by priority can be variable, accounting production specifics, the process of the criteria analysis becomes more complicated. The purpose of the work is to create a generalized methodology for the criteria analysis of multivariant systems, the meaning of which is to detect parameters that are most important in real conditions at the moment of making an informed decision, with further analysis under prioritized parameters.

The result of the system analysis should target the provision of efficiency of the analyzed system in the conditions of accepted limitations and priorities. The sequence of the selection of the optimal variant of the production system is determined by the economical, technical and organizational tasks. When designing, it is necessary to understand that any processing solutions can be and should be changed or adjusted during the implementation at the executive stage of production. The difficulty and labour intensity of the whole process of multivariant system design is the comparison of efficiency and profitability of various options. With this, the comparison of equivalent options is necessary at every stage of design. The degree of depth and structure of production system depends on the type of production.

Research methodology

To formalize the problem, let's use the basics of matrix analysis.

Let O_i be the facilities or systems for comparison, where i varies from 1 to m, and m is the number of facilities/systems for comparison. The parameters, characterizing the comparison systems, are marked as P_j, where j varies from 1 to n, and n is the number of parameters, selected for comparative analysis. In this way, $O_i = O_1, O_2, \ldots O_m$; $P_j = P_1, P_2, \ldots P_n$, $P \in O$.

As each criterion usually has its own dimension, to make matrix computation more convenient, considering the priority of the minimal or maximal value of a criterion, let's represent the entries of the matrix as the non-dimensional value a_{ij}. For encoding, it is necessary to rank the indicators of Pj into those, preferable in the maximal value (increasing is required), and those preferable in the minimal value (decreasing is required).

If the maximal value of the criterion in the specified comparison conditions, is more preferable, the matrix entry a_{ij} in the encoded view will have a non-dimensional numeral value equaling the module of the criterion value $a_{ij} = \left| P_{ij} \right|$. In case the minimal value of the comparison criterion is preferred, let's take a_{ij} as a non-dimensional numeral value equaling the module of the reciprocal value of the criterion $a_{ij} = \left| \frac{1}{P_{ij}} \right|$.

To implement the method, let's make the incident matrix $M(a_{ij})$, the rows of which will represent the facilities or systems of comparison O_i, and the columns will represent the criteria P_j, characterizing these facilities or systems of comparison.

$$M(a_{ij}) = \begin{matrix} & P_1 & P_2 & P_3 & \dots & P_n \\ O_1 & a_{11} & a_{12} & a_{13} & \dots & a_{1n} \\ O_2 & a_{21} & a_{22} & a_{23} & \dots & a_{2n} \\ O_3 & a_{31} & a_{32} & a_{33} & \dots & a_{3n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ O_m & a_{i1} & a_{i2} & a_{i3} & \dots & a_{mn}. \end{matrix} \quad (1)$$

The recommended construction of the matrix allows performing the comparison, analysis and rational selection of the facility or the system, taking into account the previous ranking of parameters.

Further on, the criteria can be represented both by discrete numeral values and functional dependencies $P = f(k_z)$ from the parameters $k = \{k_1, k_2, \dots, k_z\}$, which, by the moment of decision making, take specific values depending on the limitation, selected by users, which meet the conditions of comparability specific for enterprise organization. The selection of the number and content of the parameters depends on a specific situation and on the type of the considered facility or system.

It is worth mentioning that the more parameters, characterizing the analyzed facilities, are taken for calculation, the more informed selection of the rational decision will be made.

The incident matrix, made under the above-mentioned methods, allows calculating the weighting criteria coefficient q_i for every i^{th} facility or comparison system individually.

$$q_i = \sum_{j=1}^{n} a_{ij}. \quad (2)$$

The values, received in the result of the calculation, are formed into the resultant vector:

$$q = \begin{pmatrix} q_1 \\ q_2 \\ \dots \\ q_i \end{pmatrix}. \quad (3)$$

The resulting vector allows visually judging on the rationality of every comparison facility, where the maximal value q_i indicates a higher priority of the solution.

Results and Discussion

As an example of the practical use of the proposed method, let's perform a comparative analysis of the process of edge cutting machining of the *STEF-1* fiber-glass polymer composite material with an interlocking side mill carrying various insert materials.

STEF-1 fiber-glass laminate is a multi-layer material based on fiber-glass, impregnated with an epoxyphenol binder. As a rule, edge cutting machining of polymer composites is challenging when providing the required quality of processed surfaces and physical and mechanical properties of parts [27–32]. It is connected with the structure of polymer composites and the special features of its behavior in mechanical effect of the cutting blade. The process of composite cutting differs from cutting metallic materials, and it is not always possible to apply conventional approaches when selecting an edge tool [27, 29].

When processing composite polymers with cutting, tool materials should have specific physical and mechanical properties, have high wear resistance and hardness, which provides the performance of the tool and increases the production efficiency [33, 34].

To perform multi-criteria analysis under the proposed methods, the following allowances and limitations are accepted. The constructions of the tools (facilities for comparison O_i) have the similar design and geometrical parameters, selected under the previous studies [27, 29, 33, 34], but differ in the material of the cutting part, equipped with the following tool materials: *WC-2Co*, *WC-8Co*, *WC-15Co*, *WC-3Co*, *WC-2TaC-6Co*, *WC-5TiC-10Co*.

Under the previous studies, in order to improve the conditions and reduce the periods of organizational and technological preparation of the cutting tool when implementing the processing technologies, achieving rational tool performance in conjunction with ensuring the required quality of the machined surface and intensifying the processing performance of polymer composite materials, it is recommended to use:

1. High-tensile tool materials to equip the cutting part of the instrument. The options for the tool materials are specified above.

2. Cutting modes when processing composite materials: feed per tooth S = 0.15…0.17 mm/tooth, depth-of-cut t = 0.5…0.6 mm, rotations n = 6 000 min^{-1} – with these parameters, the maximal cutting speed is achieved (within the limits allowed by processing equipment).

3. Geometrical parameters of the tool are set within the following limits: rake angle γ = 15…20°, clearance angle α = 10…15°, taper angle β = 55…60°.

The cost of carbide blades for mills were received from *Kirovgrad Hard Alloys Plant*. The cost of the mills is calculated at high level considering the cost for the production under the laboratory conditions.

The physical and mechanical properties of the tool materials are given for reference only.

The baseline data for analysis are presented in Table 1.

At present, the rational selection of the tool material for the specified enterprise conditions is a necessary stage of production design process. The performance criteria of edge cutting machining technology of polymer composites include the following: the functional capability, performance and economic efficiency.

The blade life is the parameter of the functional capability of a cutting tool. The definition of this value depends on significant values for such processing parameters as technological cutting modes, tool materials, workpiece material properties, the geometrical parameters of the tool. Taking the results of the blade life tests at the given combination of the workpiece material and tool material (experimental system) as the input data, it is possible to determine the calculated (predicted) blade life of the cutting tool at any combination of materials (calculation system) as follows [27]:

$$T = T_e K_T \text{, min,}$$

where – the experimental period of blade life at the known combination of the materials, min; K_T – coefficient of variation of the blade life period, which depends on the combination in the tool system of the physical, mechanical and operational parameters of the tool and the workpiece material, studied (predicted) and obtained empirically earlier.

The complete calculation of production efficiency and functional capability of the tool is made under the developed method [27, 29]. When determining the criterion of economic efficiency, it is necessary to determine production costs. The calculation of economic effect is made under the developed method [35].

The results of the calculation are presented in Table 2.

Table 1

Form factors of compared cutters

Parameters	Parameter value					
Construction code	O_1	O_2	O_3	O_4	O_5	O_6
Cutting material	WC-2Co	WC-8Co	WC-15Co	WC-3Co	WC-2TaC-6Co	WC-5TiC-10Co
Cutter diameter, mm	250					
Cutter cost, rubles	4,500					
Number of teeth, pcs	4					
Number of cutting element switches	50					
Cutting width, mm	10					
Rake angle, γ°	20					
Clearance angle, α°	12					
Sharpening time of one cutting element, min	1.5					
Cutting mode	S = 0.15…0.17 mm/tooth, t = 0.5…0.6 mm, n = 6 000 min^{-1}					
Compressive resistance, MPa	3,900	3,910	2,800	4,700	4,900	3,000
Hardness, HRA	91.5	88.0	86.0	91.5	90.5	88.5
Elasticity modulus, GPa	645	598	559	638	632	549
The price of one cutting element, rub.	63	66	54	95	95	45

Let's consider the production condition, in which it is necessary to provide high operating capacity of the cutting tool and to increase the production efficiency, while reducing production costs. Consequently, the operating capacity and the performance will have a dimensionless numerical value $a_{ij} = \left|P_{ij}\right|$, equal to the modulus of the criterion value; and the production costs – a non-dimensional numerical value, equal to the modulus of the reciprocal value of the criterion $a_{ij} = \left|\frac{1}{P_{ij}}\right|$. After ranking the criteria, let's make an incident matrix.

$$M(a_{ij}) = \begin{pmatrix} & T & P & R_z & PZ \\ Q_1 & 61.26 & 16.15\cdot10^{-5} & \frac{1}{23} & \frac{1}{6.26} \\ Q_2 & 39.29 & 10.36\cdot10^{-5} & \frac{1}{23} & \frac{1}{9.76} \\ Q_3 & 22.65 & 5.97\cdot10^{-5} & \frac{1}{23} & \frac{1}{16.93} \\ Q_4 & 76 & 20.04\cdot10^{-5} & \frac{1}{23} & \frac{1}{5.098} \\ Q_5 & 71.67 & 18.9\cdot10^{-5} & \frac{1}{23} & \frac{1}{5.41} \\ Q_6 & 34.05 & 8.98\cdot10^{-5} & \frac{1}{23} & \frac{1}{12.74} \end{pmatrix}.$$

Table 2

Production criteria calculation results

Parameters	Parameter value					
Construction code	O_1	O_2	O_3	O_4	O_5	O_6
Blade life T, min	61.26	39.29	22.65	76	71.67	34.05
Production efficiency P, 10^{-5} m^3/min	16.15	10.36	5.97	20.04	18.9	8.89
Reduced costs, PZ, 10^{-3} rub/mm^3	6.26	9.76	16.93	5.098	5.41	12.74
Surface finish, R_z µm	23					

The following values will be obtained:

$$M(a_{ij}) = \begin{pmatrix} & T & P & R_z & PZ \\ Q_1 & 61.26 & 16.15\cdot10^{-5} & 0.043 & 0.16 \\ Q_2 & 39.29 & 10.36\cdot10^{-5} & 0.043 & 0.10 \\ Q_3 & 22.65 & 5.97\cdot10^{-5} & 0.043 & 0.06 \\ Q_4 & 76 & 20.04\cdot10^{-5} & 0.043 & 0.20 \\ Q_5 & 71.67 & 18.9\cdot10^{-5} & 0.043 & 0.18 \\ Q_6 & 34.05 & 8.98\cdot10^{-5} & 0.043 & 0.08 \end{pmatrix}.$$

Considering the fact that the roughness value is the same for every facility, its value can be ignored. To calculate the weighting criteria coefficient q_i for every i^{th} facility of comparison individually, let's calculate the selected criterion under the formula (2).

$$q_1 = 61.26 + 16.15\cdot10^{-5} + 0.16 = 77.57\cdot10^{-5}$$

$$q_2 = 39.29 + 10.36\cdot10^{-5} + 0.10 = 49.75\cdot10^{-5}$$

$$q_3 = 22.65 + 5.97\cdot10^{-5} + 0.06 = 28.68\cdot10^{-5}$$

$$q_4 = 76 + 20.04\cdot10^{-5} + 0.20 = 96.22\cdot10^{-5}$$

$$q_5 = 71.67 + 18.9\cdot10^{-5} + 0.18 = 90.75\cdot10^{-5}$$

$$q_6 = 34.05 + 8.98\cdot10^{-5} + 0.08 = 43.1\cdot10^{-5}$$

The resulting values of the weighting criteria coefficient are formed into the resulting vector for the analyzed design of the cutting tool:

$$q = \begin{vmatrix} 77.57\cdot10^{-5} \\ 49.75\cdot10^{-5} \\ 28.68\cdot10^{-5} \\ 96.22\cdot10^{-5} \\ 90.75\cdot10^{-5} \\ 43.10\cdot10^{-5} \end{vmatrix}.$$

Thus, resulting from the comparative multi-criteria analysis a conclusion can be made on the priority in the considered system with the specified parameters of technology implementation of the construction O_4

equipped with *WC-3Co* alloy, which shows the largest value of the *q* coefficient. When making the incident matrix, the prevalence of this design of the cutting tools over the similar ones under the selected criteria has already been observed. It also confirms the illustrative purpose of the selected method. Under the results of the analysis, the tool equipped with *WC-6Co* alloy is close in rationality, which allows recommending it as an analogue in the process of choosing.

The presented example of rationality of milling composite materials is limited only with the choice of materials of the cutting part of the tool. In real production settings, the technical process includes a large number of parameters and criteria, which should be ranked under the production conditions.

Conclusion

This methodology provides the possibility of creating production facilities or systems based on the existing ones by various events using the temporary organizational connections without labor-consuming physical reconstructions. This is a new approach to the formation of a production system with the required features. The process of developing the design solution includes subsequent actions to propose, estimate and correspondingly select mutually exclusive alternatives. The task to select the optimal option is solved by using the general knowledge of the challenging media and the internal model of any system as well as by implementing the targeted search with the exclusion of knowingly unacceptable decision from consideration.

1. The scope of the proposed implementation of the methodology is appeared if it is necessary to analyze complex multivariant systems/facilities.

2. The objects/systems can be both variants of scientific solutions under various conditions of comparability, as well as design, technological solutions, structural and instrumental materials at the selection stage in the design and technological preparation of production, variants of the system implementation algorithm.

3. Physical and mechanical, processing and operation parameters, technical, economical and quality indicators, specific features and parameters can act as comparison parameters.

4. The proposed methods allow reducing the time for making new solutions in varying production conditions and determining correlation of design stages.

The use of the methodology with the known and clearly defined parameters, characterizing multivariant systems, allow algorithmizing and further automating the process of organizational and technological preparation of production. It will significantly reduce the time and increase the quality of the multi-criteria comparative analysis of systems and making informed decisions (scientific or industrial) under the varying comparison conditions.

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Conflicts of Interest

The authors declare no conflict of interest.