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Methods of automated control over composition and structure of metalworking equipment

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Abstract. The technique of automated control over the composition and structure of metalworking equipment is examined based on a set of criteria. Multitude of alternative structures and technical and economic solutions to the problem of overhaul or local re-equipment of production is formed on the basis of the developed multi-layer graph model. The generated mathematical model is defined on the set of Boolean variables and implemented using linear programming methods. The choice of an effective composition and structure of technical means for equipping technological operations is based on the results of an analysis of evaluation criteria that determine technical, economic, production and financial indicators of an industrial enterprise, as well as partial indicators of quality and competitiveness of production facilities.

1 Introduction

Innovative overhaul of machine-building production, which includes the basic technological conversion (harvesting, processing, assembly, testing, logistics, pre-production, etc.), is a resource-intensive task that requires scientifically based estimates and solutions. Formation of traditional technological processes for manufacturing of machine-building components requires a broad production base. The compactness of the structure and minimum resource intensity of equipment for processing industries depends on the adopted paradigm of synthesis of processing systems [1-3].

Serial production is characterized by a wide range of metalworking equipment. In these conditions, it is necessary to use analytical methods to automate formation and selection of technical means for equipping forming operations based on their efficiency.

Typical metalworking production includes the following main groups of machines: turning, milling, multi-purpose, gear-processing, grinding machines etc. For efficient loading, it is important to equip these machines with a wide range of cutting tools whose cost per lifetime often exceeds the cost of the machine by several times. With that in mind, it is important to justify the structure of the instrumental support, which is necessary and sufficient not only in terms of production indicators (forming, recovery), but also in terms of value. On the other hand, the overhaul of machines is a very costly item of the

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company's expenses and is often done ‘by analogy’, that is, to replace the obsolete ones. However, this approach is not justified in connection due to rapid improvement of the tool and development of new progressive forming technologies that require the use of modern innovative equipment capable of supporting new processing methods in terms of kinetic, energy and shape-forming parameters. Thus, the structure of machinery should be updated based not only on resources, but also on technical and economic indicators such as precision, productivity, reliability, cost-efficiency etc.

The complexity of the task of managing the operating activities of an enterprise in this case is determined by the need to identify and establish a large number of complex interactions between the parameters of production processes, technological equipment parameters and parameters for assessing the efficiency of industrial activities, taking into account the dynamically changing environmental factors [4-7]. The key task here is the procedure for synthesizing the solutions to the problem with the subsequent evaluation of alternatives according to the selected criteria, taking into account all the restrictions [8-11].

The aim of this study is to develop a method for automated management of composition and structure of metalworking equipment on the basis of a set of mathematical models.

To achieve the set objective, the following research tasks are stated in the paper: to develop a mathematical model for putting together a multitude of options for the composition and structure of technical equipment; to justify the selection of a set of criteria for choosing the optimal option; to develop a mathematical optimization model for selecting the composition and structure of technical equipment based on a set of preference criteria.

2 General provisions of methods of automated control over composition and structure of metalworking equipment

To achieve objectives set in this study, it is suggested to use the basic laws of development and synthesis of technological forming systems, which underlie metalworking; for instance, directed synthesis of the processing system using the constants of complexities of basic system components (machine and cutting tool).

Modern trends in the development of the processing technological environment at machine-building enterprises show that there are two basic types of forming technologies in metalworking. The first type of shaping is carried out with the tool barely touching the workpiece, which is done with the help of complex multi-axial kinematics of a machine with a simple form of the cutting tool. Advantages of this method are wide shape-forming possibilities for processing of curvilinear extended or hard-to-reach surfaces, which is canceled out by low precision of processing due to the large number of simultaneously interpolated machine coordinates and the compliance of the cantilever tool at bending deformations, as well as the significant processing time due to multipass.

The second method is based on the profile scheme of metal removal with the linear contact of the tool with the workpiece, causing greater productivity and high accuracy due to simplification of the machine kinematics and favorable effect of force on the compression tool.

The aforementioned motivates a technologist to optimize the structure and innovative composition of the set of technological equipment for a particular type of production where processing technologies will be implemented in the most effective way, reducing the cost of production.

The objective is to synthesize such a structure of machinery in combination with the corresponding tooling, which would have the maximum technical and economic effect. At the same time, the best solutions are selected on the basis of optimization functions which are, in turn, form the basis of technical and economic criteria. Functional and cost parameters of components of enterprise’s technological environment are controlled parameters of the model (in particular, the properties of form-building systems, machines and tools, the values of which are known).

Multitude of alternative structures and technical and economic solutions to the problem of overhaul or local re-equipment of production is formed on the basis of the developed multi-layer graph model. Each layer of the graph determines any phase or stage of manufacturing a workpiece, and depth of the layer determines possible variants of the structures of the forming systems, enlarged by the set of metal working machines and cutting tools. It should be noted that when forming a network structure for a certain set of machines and tools, for example using manufacturers' catalogs, the number of variants of structures is the final value. When forming a network model that conceptually describes a class of parts or surfaces to be processed, the quantities that determine the number and depth of the layers will be infinite. The latter should be taken into account in order to ensure the uniformity of the network structure and indexing of its vertices when it is supplemented with new structural features or variants of their implementation, which is necessary for the creation of new products.

Thus, the set of layers and their depths forms the set of vertices of the network graph x_{ij}, where x is the name of the variable reflecting a structural element of the forming system, i is the variable characterizing the sequence number of the graph layer; j is the variable characterizing the depth of the i-th layer of the graph [12-14].

Further formation of the network structure is carried out by determining the bypass of the graph, the number of which corresponds to a set of possible variants of the structural arrangements of the forming systems:

$$K_i = x_s \bigcup_{i=1}^{n} \bigcup_{j=1}^{m} x_{ij} \bigcup x_t \tag{1}$$

while the multitude of types of composition may be determined by multiplying the multitude of graph vertices:

$$M_{K_i} = x_s \cdot x_t \prod_{i=1}^{n} \prod_{j=1}^{m} x_{ij} \tag{2}$$

The sum of the complexities of the components interacting within the system is a constant value, so it allows you to superimpose weights on the edges of the graph and synthesize the composition and structure of enterprise’s technological equipment in the form of the following mathematical model:

$$\begin{cases} \sum_{j=1}^{m} x_{ij} = 1, \ \forall i \in \{1,2,...,n\} \\ \sum_{i=1}^{n} x_{ij} = 1, \ \forall j \in \{1,2,...,m\} \end{cases} \\ x_{ij} = \{0,1\}, \ (\forall i \in \{1,2,...,n\}, \forall j \in \{1,2,...,m\}) \tag{3}$$

The generated mathematical model (3) is defined based on the set of Boolean variables and implemented using linear programming methods.

The economic effect after introduction of the optimal equipment composition for equipping technological operations, automation and information and communication facilities can be divided into direct and indirect. Direct economic effect is understood as saving of material and labor resources and the improvement of quality of products manufactured after optimization of the production activity of the enterprise. Indirect effect is achieved by optimizing the off-production activities of the enterprise, which determines cost reduction for the functions of enterprise management. Within the framework of this study, modeling and analysis of direct economic effect is analyzed.

Broadly speaking, industrial activity of the enterprise may be determined by the technical preparation of production, which characterizes measures aimed at improving quality of the products; preparation and organization of technical and technological means of production automation; a set of technological processes for manufacturing products based on the operation of equipment for equipping technological operations; a set of intra- and out-of-production logistics activities that ensure fulfillment of production tasks.

The efficiency of production activity of an industrial enterprise can be comprehensively determined by the method of a Real Option Valuation (ROV), which allows to study the whole sum of activities conducted during the life cycle of innovation [15]. Then the investment value of the enterprise should be calculated according to the following equation:

$$C = C_{ie} + C_{ROV} \tag{4}$$

where C_{ie} - the enterprise value without option valuation; C_{ROV} - is the option value.

Within the framework of this study, a set of innovative measures aimed at introducing into the production process the optimal composition of technological equipment as well as computing, automation and information and communication facilities that increase the efficiency of production processes, the quality and competitiveness of the products.

When studying model (4), it was assumed that at the initial stages of decision-making cost C_{ie} is a constant value that only affects the absolute value C and does not influence the choice of option development [15]. During decision-making, the following variants of option development were considered: a development option adding value to the enterprise under consideration, as it allows to obtain additional profit (CALL option); an option to replicate the operational experience, showing the possibility of using previous experience in future enterprise development projects; an option to delay the beginning of the project, which determines the possibility to postpone investment until new information is available to take informed decisions; an option to exit from business in case of running at a loss (PUT option), and an option for switching and temporary stopping of business in case of a sum of unfavorable factors. In its basic arrangement, value of CALL option is calculated based on the Black-Scholes model [15]:

$$C_{опц} = PN(d_1) - Se^{-rt}N(d_2) \tag{5}$$

Here P - total value of enterprise's assets; S - the value of option exercising; t - the time of option exercising; r - the riskless interest rate; e - the exponent (2,7183); σ - the SD of total value of asset deviation.

$$d_1 = \frac{\ln\left(\frac{P}{S}\right) + \left(r + \frac{\sigma^2}{2}\right)t}{\sigma\sqrt{t}}, \quad d_2 = d_1 - \sigma\sqrt{t} \tag{6}$$

Model (6) is implemented for the following assumptions: the price of the enterprise's assets is a continuous value; the standard deviation is known and does not change during the lifetime of an option; the underlying asset (a project of automation and informatization of an enterprise) is not traded openly on the market.

The choice of an effective composition and structure of technological equipment should be carried out based on the analysis of evaluation criteria determining the technical, economic, production and financial indicators of an industrial enterprise, as well as partial indicators of quality and competitiveness of production facilities with a given option:

$$
\begin{aligned}
& F_k = \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} b_{ij} \rightarrow min(max), \begin{pmatrix} \forall k \in \{1,2,...,l\} \\ \forall i \in \{1,2,...,n\} \\ \forall j \in \{1,2,...,m\} \end{pmatrix} \\
& F_{ad} = \sum_{k=1}^{l} \frac{F_k}{F_{kex}} K_{s_k} \rightarrow min(max) \\
& \begin{cases} \sum_{j=1}^{m} x_{ij} = 1, \ \forall i \in \{1,2,...,n\} \\ \sum_{i=1}^{n} x_{ij} = 1, \ \forall j \in \{1,2,...,m\} \end{cases} \\
& x_{ij} = \{0,1\}, \ \left(\forall i \in \{1,2,...,n\}, \forall j \in \{1,2,...,m\}\right)
\end{aligned}
\tag{7}
$$

Here F_k is the sum of partial target functions of elements of enterprise's equipment; F_{ad} is the target function of complex efficiency criterion; K_{sk} is the significance of k-th partial target function; c_{ij} is the degree of conformity of each synthesized option to k-th conformity criterion (weight of graph edges); b_{ij} is the numerical value of technological and economic features of components of enterprise's equipment system (in nominal points).

If there is one preference criterion, the task of choosing an optimal structure of enterprise's equipment is reduced to finding the minimum or maximum path in the graph corresponding to the minimum or maximum value of the partial objective function.

If it is necessary to take into account a set of preference criteria, the choice of the optimal variant is reduced to the calculation of the additive convolution of particular criteria. When forming convolutions of particular criteria, the nature of the objective functions should be taken into account, in particular, tendency to a maximum or a minimum. In order to reduce the influence of the unequal character of absolute values of individual objective functions on the final result during formation of additive convolution, it is necessary to scale the values of the objective functions of the preference criteria relative to their given possible extreme values F_{kex}.

3 Implementation of methods

When implementing the developed models (4) - (7) and methods, software like MS Excel, MS Visual Studio, MS Access, C#, and MS SQL was used.

The developed models and tools were used to design software for the development of enterprises in the real sector of the economy; for instance, during preparation of projects aimed at developing a separate division of a full-cycle machine plant, expanding existing machine production and production capacities of a machine-building enterprise etc.

4 Conclusion

As a result of this study, the method of the automated management of composition and structure of equipment used in metal-working has been developed.

The basis of this method is a set of mathematical models for the formation and selection of the optimal variant for a set of partial and complex preference criteria.

Industrial approbation of this method has shown its efficiency and flexibility in solving various problems of technical overhaul of industrial enterprises.

Further development of this method presupposes a comprehensive analysis and consideration of personalized specific criteria and limitations of specific processing equipment and equipment.

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