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Additive Optimization Method for Choosing CNC Machines for Technological Preparation of Machine-Building Production

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Abstract. The introduction of Industry 4.0 into the technological preparation of production leads to the optimization of processes, including the processes of selecting equipment and tools, reducing cycle time, and reducing costs. Technological preparation of production involves a set of works that make it possible to start manufacturing a new product in a given volume. Features of technological preparation of production when using CNC machines follow from the fact that a significant part of the work from the sphere of direct production is transferred to the area of its technological preparation. Technological preparation of production plays an important role in the successful functioning of a machine-building enterprise. Optimization of equipment selection allows you to increase productivity, reduce costs and improve product quality. The use of modern optimization methods and information technology allows you to make this process more efficient and accurate. The article provides a methodology for calculating the additive criterion for optimizing the selection of the best option for CNC machines.

Keywords: CNC machines, industry 4.0, mechanical engineering, mathematical model, production optimization.

Introduction

The selection of CNC machines is one of the key stages of technological preparation of mechanical engineering production [1]. The efficiency of production, product quality and competitiveness of the enterprise depend on the correctness of this choice [2]. Traditionally, various expert methods and software products based on a comparative analysis of the technical characteristics of the machines were used to solve this problem [3]. CNC machines are capable of performing operations with high accuracy and repeatability, which is especially important in the production of parts with complex geometry and high requirements for surface quality [4]. Automation of processes for processing parts on CNC machines can significantly reduce production time and increase the volume of manufactured products. The ability to quickly reconfigure machines for the production of new products ensures high flexibility of production and allows you to quickly respond to changes in the market situation [5]. Automation of manual operations leads to a decrease in labor costs and an increase in productivity. CNC machines allow you to obtain products with higher surface quality and dimensional accuracy, which reduces the amount of defects and increases the competitiveness of products. Due to the high accuracy of CNC machine processing, the amount of material waste is reduced. CNC machines allow processing parts with complex geometry, which are impossible to manufacture on universal machines [6].

Selecting the best option under a variety of conditions is a problem of multi-criteria optimization under conditions of complete certainty [7]. Mathematical models describing the systems under study can be presented in the form of tables containing the values of individual criteria for various strategies under strictly defined external conditions [8]. In such a situation, a decision can be made either based on one most significant criterion, or taking into account a set of several criteria [9].

One of the approaches to solving multi-criteria control problems is associated with the procedure for forming a generalized function Fi, monotonically dependent on a number of criteria [10]. This procedure is called the procedure (method) of criteria folding [11]. There are several folding methods, but the most commonly used is the additive optimization method [12].

The additive optimization method allows, when selecting CNC machines during the technological preparation of mechanical engineering production:

- to take into account a wide range of factors influencing the choice of machines;
- minimizes the subjectivity of decision-making;
- can be adapted to various production conditions and product ranges;
- allows finding the optimal solution in the shortest possible time.

The purpose of the article is to select the best five-axis CNC machine based on the criteria of performance, cost, memory capacity, reliability and using the additive optimization method.

1. Research Methodology

The additive optimization criterion (generalized objective function) is determined by the formula [13]:

$$F_i(\alpha_{ij}) = \sum_{j=1}^{n} \partial_i \alpha_{ij} \quad (1)$$

where ∂_i – weight coefficient;

α_{ij} – private criteria.

The values ∂i are weighting coefficients that quantify the degree of preference of the i-th criterion over other criteria. In other words, the coefficients ∂i determine the importance of the i-th optimality criterion. In this case, the more important criterion is assigned a higher weight, and the total importance of all criteria is equal to one, i.e. [14]:

$$\sum_{i=1}^{n} \partial_i = 1, \partial \geq 0, i = \overline{1,n}$$

The generalized objective function (1) can be used to convolve private optimality criteria if [15]:

- private (local) criteria have equal quantitative importance, i.e., each of them can be assigned to some number ∂i, which numerically characterizes its importance with respect to other criteria;
- private criteria are homogeneous (have the same dimensionality).

In this case, the application of the additive optimality criterion is valid for solving the multicriteria optimization problem If the given local criteria are not homogeneous, i.e., they have different units of dimension, in this case, the application of the additive optimality criterion is valid.

have different units of dimensionality, in this case normalization of criteria is required.

Criterion normalization means such a sequence of procedures, by means of which all criteria are brought to a single, dimensionless scale of measurement.

For normalization it is necessary to determine the maximum and minimum of each local criterion, i.e.:

$$\alpha_j^{+} = \max \alpha_{ij}, i = \overline{1,m},$$
$$\alpha_j^{i} = \min \alpha_{ij}, i = \overline{1,m}.$$

We distinguish a group of criteria $\alpha_j, j = \overline{1,1}$, which are maximized when solving the problem, and a group of criteria $\alpha_j, j = \overline{1^{+1},n}$, which are minimized when solving the problem. Then, in accordance with the principle of maximum efficiency, the normalized criteria are determined from the following relations:

$$\widehat{\alpha_{ij}} = \frac{\alpha_{ij}}{\alpha_j^{+}}, j = \overline{1,1},$$
$$\widehat{\alpha_{ij}} = 1 - \frac{\alpha_{ij}}{\alpha_j^{+}}, j = \overline{1+1,n},$$

$$\widehat{\alpha_{ij}} = \frac{\alpha_{ij} - \alpha_j^{-}}{\alpha_j^{+}}, j = \overline{1,1},$$
$$\widehat{\alpha_{ij}} = \frac{\alpha_i^{+} - \alpha_{ij}}{\alpha_j^{+} - \alpha_j^{-}}, j = \overline{1,1}n.$$

The optimal option (strategy) is the one that maximizes the value of the objective function (1):

$$F_i = \sum_{j=1}^{n} \partial_i \cdot \widehat{\alpha_{ij}}, j = \overline{1,m} \qquad (2)$$

According to the principle of minimum loss, the normalized criteria are determined from the relation:

$$\widehat{\alpha_{ij}} = 1 - \frac{\alpha_{ij}}{\alpha_j^{+}}, j = \overline{1,t},$$
$$\widehat{\alpha_{ij}} = \frac{\alpha_{ij}}{\alpha_j^{+}}, j = \overline{t^{+1},n},$$
$$\widehat{\alpha_{ij}} = \frac{\alpha_j^{+} - \alpha_{ij}}{\alpha_j^{+} - \alpha_j^{-}}, j = \overline{1,t},$$
$$\widehat{\alpha_{ij}} = \frac{\alpha_{ij} - \alpha_j^{-}}{\alpha_j^{+} - \alpha_j^{-}}, j = \overline{t^{+1},n}.$$

In this case, the optimal option (strategy) will be the one that provides the minimum value of the objective function (2).

The considered approach to solving multicriteria problems is often used in solving technical and economic problems related to technological preparation of production

2. Results and discussion

Suppose that in the conditions of a machine-building enterprise engaged in manufacturing of complex-shaped parts, it is required to choose an optimal strategy for providing new production with five-axis CNC machines. The following equipment was chosen as analogs:

- NL635T (SL6315T) CNC turning machining center, SOLEX, China (equipment 1);
- CNC turning machining center LT 30/1000, Ace Micromatic, Germany (equipment 2);
- turning machining center with CNC VR 8, HAAS, USA (equipment 3);
- CNC turning machining centers TAKISAWA EX, Japan (equipment 4).

With the help of statistical data and information of the relevant manufacturing plants having such equipment, local criteria for the functioning of the required equipment were determined.

By means of experimental observations, the values of private criteria of functioning of the corresponding equipment (αij) were determined, which are shown in Table 1.

The data for choosing the optimal strategy are considered under conditions of full certainty.

Table 1. Partial criteria of CNC machine tool utilization efficiency

Equipment options (solution strategies)	Partial criteria of equipment efficiency			
	Performance, f.u	Cost of equipment, f.u	Memory capacity, c.u.	Reliability, c.u
Equipment 1 (X_1)	α_{11} = 100	α_{12} = 5	α_{13} = 5	α_{14} = 8
Equipment 2 (X_2)	α_{21} = 150	α_{22} = 6	α_{23} = 8	α_{24} = 5
Equipment 3 (X_3)	α_{31} = 120	α_{32} = 4	α_{33} = 7	α_{34} = 6
Equipment 4 (X_4)	α_{41} = 200	α_{42} = 7	α_{43} = 6	α_{44} = 4
Note: f.u. – fraction of units; c.u. – conventional units				

The weighting coefficients of private criteria were also determined on the basis of expert assessments ∂_i, $i = \overline{1,n}$:

∂_1 = 0,25; ∂_2 = 0,2; ∂_3 = 0,32; ∂_4 = 0,23.

Obviously, the choice of the optimal strategy (equipment variant) by one criterion in the task is not difficult. For example, if we evaluate the equipment by reliability, the best is equipment 1 (strategy X1).

If it is necessary to choose the optimal equipment variant by two homogeneous local criteria:

- productivity (f.u.);
- equipment cost (f.u.).

Let the weight coefficients of these two partial criteria have been determined on the basis of expert evaluations: ∂1 = 0.665, ∂2 = 0.335. Let us calculate the additive optimality criterion for the three variants:

$$F_i(\alpha_{1j}) = \partial_1\alpha_{11} + \partial_2\alpha_{12} = 0{,}665 \cdot 100 + 0{,}335 \cdot 5 = 68{,}175$$

$$F_i(\alpha_{2j}) = \partial_1\alpha_{21} + \partial_2\alpha_{22} = 0{,}665 \cdot 150 + 0{,}335 \cdot 6 = 103{,}09$$

$$F_i(\alpha_{3j}) = \partial_1\alpha_{31} + \partial_2\alpha_{32} = 0{,}665 \cdot 120 + 0{,}335 \cdot 4 = 81{,}15$$

$$F_i(\alpha_{4j}) = \partial_1\alpha_{41} + \partial_2\alpha_{42} = 0{,}665 \cdot 200 + 0{,}335 \cdot 7 = 135{,}345$$

Obviously, the fourth variant of equipment according to the two private cost criteria will be optimal, since Fmax = F4(a_{ij}) = 135.345.

In the problem under consideration, the four local criteria are not homogeneous, that is, they have different units of measurement.

In this case, it is necessary to determine the optimal strategy of equipment selection from four possible (m = 3) taking into account the four local criteria (n = 4).

The evaluation of the choice of the optimal variant is carried out according to the algorithm (Figure 1).

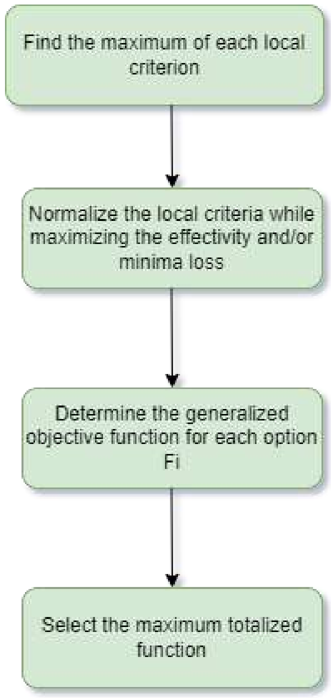

Fig. 1. - Selection of the optimal option based on the additive criterion

1. Determine the maximum of each local criterion:

$$\partial_1^+ = 200;\ \partial_2^+ = 7;\ \partial_3^+ = 8; \partial_4^+ = 8$$

2. When solving the problem, the first criterion (productivity), the third criterion (memory capacity) and the fourth criterion (reliability) are maximized. The second criterion (equipment cost) is minimized.

3. Based on the principle of efficiency maximization, we normalize the criteria:

Productivity

$$\widehat{\alpha_{i1}} = \frac{\alpha_{i1}}{\alpha_1^+}$$

$$\widehat{\alpha_{11}} = \frac{\alpha_{11}}{\alpha_1^+} = \frac{100}{200} = 0{,}5$$

$$\widehat{\alpha_{21}} = \frac{\alpha_{21}}{\alpha_1^+} = \frac{150}{200} = 0{,}75$$

$$\widehat{\alpha_{31}} = \frac{\alpha_{31}}{\alpha_1^+} = \frac{120}{200} = 0{,}6$$

$$\widehat{\alpha_{41}} = \frac{\alpha_{41}}{\alpha_1^+} = \frac{200}{200} = 1$$

Memory capacity

$$\widehat{\alpha_{i3}} = \frac{\alpha_{i3}}{\alpha_3^+}$$

$$\widehat{\alpha_{13}} = \frac{\alpha_{13}}{\alpha_3^+} = \frac{5}{8} = 0{,}625$$

$$\widehat{\alpha_{23}} = \frac{\alpha_{23}}{\alpha_3^+} = \frac{8}{8} = 1$$

$$\widehat{\alpha_{33}} = \frac{\alpha_{33}}{\alpha_3^+} = \frac{8}{8} = 0{,}875$$

$$\widehat{\alpha_{43}} = \frac{\alpha_{43}}{\alpha_3^+} = \frac{6}{8} = 0{,}75$$

Reliability

$$\widehat{\alpha_{i4}} = \frac{\alpha_{i4}}{4}$$

$$\widehat{\alpha_{14}} = \frac{\alpha_{14}}{\alpha_4^+} = \frac{8}{8} = 1$$

$$\widehat{\alpha_{24}} = \frac{\alpha_{24}}{\alpha_4^+} = \frac{5}{8} = 0{,}625$$

$$\widehat{\alpha_{34}} = \frac{\alpha_{34}}{\alpha_4^+} = \frac{6}{8} = 0{,}75$$

$$\widehat{\alpha_{44}} = \frac{\alpha_{44}}{\alpha_4^+} = \frac{4}{8} = 0{,}5$$

4. Based on the minimum loss, we normalize the Equipment cost criterion:

$$\widehat{\alpha_{i2}} = 1 - \frac{\alpha_{i2}}{\alpha_2^+}$$

$$\widehat{\alpha_{12}} = 1 - \frac{\alpha_{12}}{\alpha_2^+} = 1 - \frac{5}{7} = 0{,}285$$

$$\widehat{\alpha_{22}} = \frac{\alpha_{22}}{\alpha_2^+} = 1 - \frac{6}{7} = 0{,}142$$

$$\widehat{\alpha_{32}} = \frac{\alpha_{32}}{\alpha_2^+} = \frac{4}{7} = 0{,}428$$

$$\widehat{\alpha_{42}} = \frac{\alpha_{42}}{\alpha_2^+} = 1 - \frac{7}{7} = 0$$

5. Determine the generalized objective function by formula (1) for each equipment selection variant:

$$F_1 = 0{,}25 \cdot 0{,}5 + 0{,}2 \cdot 0{,}285 + 0{,}32 \cdot 0{,}625 + 0{,}23 \cdot 1 = 0{,}612$$

$$F_2 = 0{,}25 \cdot 0{,}75 + 0{,}2 \cdot 0{,}142 + 0{,}32 \cdot 0{,}428 + 0{,}23 \cdot 0 = 0{,}3538$$

$$F_3 = 0{,}25 \cdot 0{,}625 + 0{,}2 \cdot 1 + 0{,}32 \cdot 0{,}875 + 0{,}23 \cdot 0{,}75 = 0{,}8085$$

$$F_4 = 0{,}25 \cdot 1 + 0{,}2 \cdot 0{,}625 + 0{,}32 \cdot 0{,}75 + 0{,}23 \cdot 0{,}5 = 0{,}6625$$

Thus it is necessary to choose equipment 3 (turning machining center with CNC VR 8, HAAS, USA), since F_{imax} = 0,8085.

In the technological preparation of production of machine-building enterprise methods as optimization methods can also be applied ideal point method, the method of the main criterion, the method of hierarchy analysis, the Pareto method and others.

These methods can be used when working with large data on processes, equipment and tools that ensure the readiness of the enterprise to produce products of the required quality at the established time, output volume and costs.

When working with a large number of criteria in selecting the optimal solution (strategy) it is possible to use specialized software packages for optimization: MATLAB, GAMS, Python with libraries, R, CPLEX, GUROBI and others.

Conclusions

1) The additive optimization method is a powerful tool for the selection of CNC machines in the technological preparation of machine-building production. It allows to make informed decisions, increase production efficiency and reduce costs.

2) The additive optimization method is used when it is necessary to consider several contradictory criteria when selecting equipment.

3) The limitation of the research of the article is the conditions of complete certainty. They assume that all parameters of the problem are exactly known. That is, the values of all coefficients, constraints and target functions are known exactly. However, in real optimization problems it is possible to encounter uncertainty conditions. In this case, such a problem should be solved using stochastic programming, robust optimization and multi-criteria optimization with uncertainty.

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