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ENSURING THE ECONOMIC EFFICIENCY OF ENTERPRISES BY MULTI-CRITERIA SELECTION OF THE OPTIMAL MANUFACTURING PROCESS

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Abstract
Technological assurance and improvement of the economic efficiency of production are the first-priority issues for the modern manufacturing engineering area. It is possible to achieve a higher value of economic efficiency in multiproduct manufacturing by multicriteria optimization. A set of optimality criteria based on technological and economic indicators was defined with the aim of selecting the optimal manufacturing process. Competitive variants and a system of optimization were developed and investigated. A comparative analysis of the optimality criteria and their influence on the choice of optimal machining processes was carried out. It was determined that the batch of parts made an impact on the selection of the manufacturing process.

Keywords
Prismatic part, multiproduct manufacturing, machining, optimality criteria, optimization, shaping intensification, profit intensity.

Introduction

In modern manufacturing engineering, a large number of engineering products obtained by machining are produced under the conditions of multiproduct manufacturing. Such type of manufacturing is characterized by instability of the batch of products and their variety [1]. In developed countries, the share of engineering products manufactured under these conditions reaches 75–80%. Multiproduct manufacturing is characterized by a wide nomenclature of products, a variety of technological operations and manufacturing routings, frequent equipment changeovers, as well as production planning.

The current level of technological development is characterized by diversity and the increased complexity of the engineering product design. It leads to increasing the requirements of the machining accuracy, which requires the use of expensive equipment and tooling, ultimately leading to higher costs and time for the design-engineering process preparation where the number of mechanisms' units and parts increases significantly, functional relationships become more complicated, and manufacturing and assembly requirements are tightened. This trend increases the complexity of the machining structure for the manufacture of parts and subassemblies, and, accordingly, leads to a labor-intensive design. This is reflected in the specific order of the machining process, thermal processing, etc.

The work of a manufacturing enterprise in the context of a market economy makes it important to ensure high-quality products at relatively low cost. This, in turn, leads to an increase in the requirements for the manufacturing accuracy of parts and assemblies, which determines the need to use expensive equipment and fixing, which ultimately leads to increased costs and time required for the production planning.

Challenge problem

The following main trends are characteristic of modern engineering:

- an increase in product output variability due to the rapid consumer market expansion;
- improving the reliability of operating characteristics, reducing the operation and maintenance cost;
- increasing requirements for product quality, parts, and processed surfaces.

Literature review

Based on current research, it was found that the main tool for improving the quality of mechanical industry products, reducing the time-frame in the product development cycle, as well as the simultaneous introduction of accuracy and manufacturing stability and, of course, minimum production costs, is the improvement of production design engineering through the development of a process planning system. Indeed, according to the research by scientists in this field [1–7], it was determined that process planning is a priority objective for product design engineering, which is almost half its labor intensity.

The paper [2] considered the special case of order release according to the iterative mechanism. The iterative mechanism is analyzed analytically for simplified formulations of the order release and lead time estimation model. Authors have shown that an order release procedure of this type that iterates on the lead times is a dual (price) coordination mechanism whose design does not meet the theoretical requirements, and there is no straightforward way to overcome this.

Papers [3] has presented perspectives on the issues of manufacturing preparation by cloud services. This research focused on the fact that at one end of the process, customers start with selecting a preferred design with the aid of artificial intelligence-based solutions, and at the other end of the process, they receive the product by means of smart logistics services.

Paper [4] has shown and analyzed the main purpose of their work in the automation processes of various current and future applications, and the challenges encountered in the design are put forward according to the characteristics of the processes. Based on the research of the requirements of composite material, process, its structure design, analysis, manufacturing technologies, verification process, maintenance, and repair, etc. the airworthiness compliance method and test planning suggestions were given, that provide technical support for primary composite airframe structure application in civil aircraft.

Numerous researches, focused on the expansion of technological capabilities of modern CNC machine tools, necessitates the improvement of design procedures in production planning [5–8]. The following papers propose the design of flexible fixtures, which provides sufficient tool availability and allows multiaxis machining of lever-type [9], fork-type [10, 11], and connecting rod-type parts [1] at one setup. Several types of research aimed at ensuring the accuracy [12], productivity [13], reliability and performance of machining [14] on CNC machine tools for crankshafts and thin-walled parts [15].

Shigemoto [16] has introduced a scope of design management that may take a mediating role to combine knowledge of engineering and marketing in the context of emotional product design. Design management in that paper was regarded to design as an artificial and creative process that aims to coordinate diverse physical factors in order to embody a conceptual solution to a social need.

As the size of Taiwan's trade enterprise and the number of the product categories it produced changed, the size of its design department was also affected, as shown by Wang and Hung [17]. In the paper, the authors have analyzed the viewpoint of the Toyota Production System (TPS) to re-explore the overall design process of the enterprise and plan a new design process. It was summarized that TPS brought considerable benefits to the company.

The research [18] has declared that the pressure exerted on the automotive industry requires the implementation of appropriate development and production measures. An optimized approach for data management between different CAD and CAE environments to support the entire vehicle body development process was introduced.

The effective technological design may only be carried out on a methodological basis for the machining optimizing [19, 20], based on feasibility principles that allow for the design and implementation of the most rational technological processes between competing options.

Kaspar et al. [19] have observed that the requested multi-objective engineering design process is difficult and time-consuming when faced with a large number of available materials and its complex relations to design as well as manufacturing and joining processes. For this specific purpose, multi-criteria decision-making (MCDM) methods are seen as one of the key factors within modern product development when designing cost-benefit optimized multi-material systems. This multi-criteria optimization process should not merely be considered on the basis of the design, materials and manufacturing processes of exclusively one single component, but tally far more closely with regard to systemic or rather cross-component aspects, and thus additionally cover such issues as the ever more relevant integrated choice of the right joining technology described in the authors' work [19].

According to these principles, the machining of parts needed to be carried out in the lowest labor and at a minimum cost provided that it is manufactured in a sufficient quantity and within the time limits established by the production schedule [21–27]. For example, in research, it was noted that time is a significant factor for business process simulation to acquire the customers' satisfaction. It is a challenging task to complete a business process of smart manufacturing companies promptly [22]. Within this framework, the next author's team has presented research results as part of the optimization of real-world unreliable unbalanced production lines where all time-based parameters are probabilistic, including the time between part arrivals, machining times, the time between failures, repair times, and setup times [23]. The same problem has been considered in paper [24], which has also proposed the new simulation-based optimization model to address the modeling and solving of the buffer and machining time optimization problem in a stochastic environment. In papers [25, 26], the authors also emphasized the need for a methodology that combines experiments with modern optimization techniques in order to solve the industrial challenge and further improve the machining quality. The main goal of the research [27] was to consider the Flexible Manufacturing System Scheduling of 80 varieties of products which were manufactured in 16 CNC machine tools by considering multi-objectiveness as the Minimization of Machine Idle time and Minimization of Penalty cost. It should be noted that the implementation of these requirements is ensured by the multivariance of the design, during which alternative options of technical positions are formed and the most profitable one is selected [28]. A part has many alternative process plans since there are many other viable machining methods and techniques. One of the forward-looking ways of solving that task is approached by Yang X. et al., whose model is based on the evaluation index system in which the quality, cost, efficiency, and environmental consumption of parts machining can be optimized [28]. However, this approach does not take the multiproduct manufacture into account.

In traditional engineering, the issue of finding suitable solutions is often not a priority due to the fact that the number of options analyzed in detail is small, and their assessment is carried out on the basis of intuition and experience of the designer, and only in a few cases by comparing the simplest quantitative criteria.

Today, the task of choosing the best technological solutions has become very relevant. This is caused, on the one hand, by the inability to improve the technology by other means, and on the other, by the capabilities of the up-to-date computer technology. Thus, favorable conditions are in place for the development and implementation of automation of the production design engineering, including that for the computer-aided engineering of the machining parts using multicriteria optimization methods. New opportunities have opened up for the directed search for effective technological solutions in the field of structural and parametric design of the manufacturing systems.

Computer-aided engineering in machining requires a review of methods for the solution of many design problems, including those of optimization, development of methods for their formalization, quantitative description, and selection of optimality criteria. Computer-aided engineering serves as an incentive for the development of formal methods for finding technological solutions and promotes the use of these methods in manual design.

Research objective

The development of competing options for the machining of a box-type workpiece and determination of the best option based on multicriteria optimization.

Research methodology

According to typical machining routes and depending on the design, technological features and the size of the production quantity, box-type workpieces can be processed on various types of milling, drilling, boring and grinding machines with manual control, or on CNC machines, using both standard and special manufacturing jigs.

The size of the production batch of parts and its design and technological features (maximum length, width, height and requirements for accuracy and surface roughness), as well as the method for producing the workpiece (rolled metal, package, die forming or molding), have a considerable influence on the choice of the machine type. The variety of metal-cutting machines on which the part can be machined and the variety of methods for the production of the part leads to an increase in the number of competitive variants. For example, for a prismatic part, shown in Fig. 1 and made from aluminum alloy ENAW-AlCuMg0.5, at least four generalized variants of machining can be generated (Table 1).

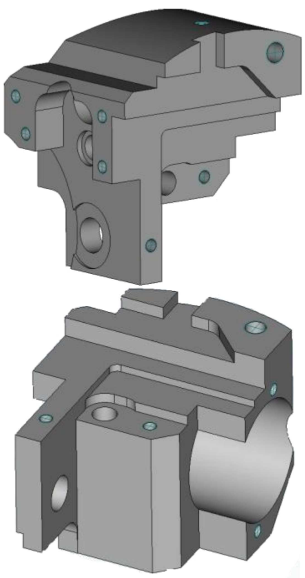

Fig. 1. Prismatic part.

Table 1
Options for the technological process of part machining.

The number of the manufacturing process	The method of obtaining the workpiece	Type of equipment
1	Rolled steel	Universal equipment with manual control
2	Molding	Universal equipment with manual control
3	Rolled steel	CNC machine tools
4	Molding	CNC machine tools

The efficiency of the enterprise's functioning is determined on the basis of a comprehensive and systematic study of its performance indicators, in which these indicators are compared, and their relationships are determined. The main indicators of enterprise activities are labor productivity, maximum profit, cost and competitiveness of products, the intensity and efficiency of the use of financial resources, material, and energy intensity of products, profitability, capital intensity, capital productivity, equipment utilization rate, etc.

The progressive development of engineering and technology, as well as increased competition among manufacturers, determine the need to intensify production. This, in turn, provides for an increase in machining productivity, an increase in the efficiency of the use of material, energy, and financial resources, an improvement in the quality of products, as well as a reduction in the time for pre-production engineering.

Thus, the determination of the most profitable variant of part machining should be carried out on the basis of a criteria system that contributes to the intensification of manufacture and characterizes the organizational and technological structure of mechanical facilities and allows for the most accurate determination of the area of the effective use of technological equipment [29].

It is advisable to use the intensity of shaping as an optimality criterion, which characterizes the organizational and technological structure of the manufacture and reflects its technical activity aspects. To assess the economic aspects of manufacture activities, it is advisable to use any of the following criteria: the intensity of marginal profit, the intensity of profit, profit, machining cost, and reduced costs.

The main criterion that makes it possible to characterize the enterprise manufacturing activity related to product manufacture is performance capacity. Process performance capacity affects most of the performance of industrial enterprises, in particular, the cost of production and profit from its sale. The increase in performance capacity and machining intensity is the most significant factor in reducing the cost of production. Thus, according to the research of the SANDVIK COROMANT company, increasing the cutting speed by 20% when machining with a tool with carbide inserts allows reducing the cost of machining by 15%, while reducing the cost of a cutting tool by 30% reduces the cost of machining by only 1%. Therefore, the most rational way to increase manufacture capacity is to increase productivity and machining intensity through the use of modern cutting materials from leading world producers, as well as special designs of cutting and auxiliary tools that are able to provide a parallel concentration of process steps.

Machining performance capacity is adequately characterized by the system criterion "intensity of shaping" W [mm/min], which, unlike the "artificial capacity" indicator, is absolute and allows to evaluate the performance capacity of various types of metal cutting machines and machine systems in the machining of various parts. This indicator has a hierarchical structure, which in turn corresponds to the structure of the technological system and the indicator "artificial capacity". The hierarchical structure of the indicator of shaping intensity consists of the technological, cyclic and regulatory intensity of shaping. The technological intensity of shaping (W_t) (minute feed) takes into account only the values of the cutting process regimes and makes it possible to identify the main machining time, and the cyclic intensity (W_c) and normative intensity of shaping (W_n) also take into account intracycle and out-cycle time losses, and, accordingly, allow to determine the working cycle time of the machine and the standard part machining time. To assess the performance capacity of machining parts on various types of metal cutting machines, it is advisable to use the normative intensity of shaping.

The objective function for determining the normative intensity of shaping has the form:

$$W_n = \sum_{j=1}^{m} \left(\sum_{i=1}^{p_j} W_{tij} \frac{t_{p\_ij}}{T_{nt\_ij} + T_{su\_j}/N_{bp} + \tau_j} \right), \quad (1)$$

where W_{t_ij} – technological intensity of forming the i-th surface on the j-th machine, [mm/min]; T_{nt_ij} – norm of floor-to-floor time of the machining of the i-th surface on the j-th machine, [min]; t_{p_ij} – main machining time of the i-th surface on the j-th machine, [min]; T_{su_j} – the setting-up time associated with the machining of a batch of parts on the j-th machine, [min]; N_{bp} – the value of the production batch of parts, [pcs]; τ_j – time reserve necessary to restore the operability of the j-th machine in case of accidental failure of the machine or tool, in order to increase the likelihood of performing work assignments, [min].

The cost criterion covers a broad array of expenditures and, along with the amount of time spent, considers the expenses materialized in the capital goods (depreciation of equipment, electricity, auxiliary materials, etc.) [30].

The production cost is determined by two main methods: 1 – the method of complete cost allocation; 2 – the method of partial cost-sharing.

When determining the cost by the method of complete cost allocation (Absorption Costing), all manufacturing expenses (fixed and variable) are taken into account in the cost of manufactured products and are proportionally distributed between the goods that are sold and goods that have not been implemented and remained in stock. By mainstreaming for fixed charges, this method provides a high level of cost, reduces the competitiveness of products.

In recent decades, the method of partial cost-sharing, the so-called Direct Costing system, according to which the cost of production is calculated only on the basis of variable costs depending on the manufacturing volume, has become widespread. Fixed charges are not included in the cost calculation, but are deducted from the total profit received during the planned time period. This is attributable to the fact that the winning and maintaining of markets are possible when selling cheaper products by reducing their cost and making a profit due to large sales volumes.

The "direct costing" system makes it possible to establish the relationship between the charges and quantity of production, namely, to predict the cost and profit, depending on them. In the direct costing system, the concept of marginal profit is distinguished, which is determined by the difference between income together with variable costs and actual profit, which is calculated by reprimanding fixed costs from the marginal profit. The change in the marginal profit allows for the identification of more profitable products and affects the range of manufactured products. Therefore, the use of the "direct costing" system in developing enterprises is a prerequisite for ensuring their sustainable development and competitiveness.

Thus, we may formulate the objective function for determining the value of the production cost of a part using the method of complete cost allocation:

$$C_p = P_w + \sum_{j=1}^{m} \left(\sum_{i=1}^{p_j} a^* + S_{w\_j} + C_{e\_j} \right) + C_F, \quad (2)$$

where

$$a^* = \frac{\left(P_{ct\_ij} + \frac{C_{C\_ij}}{z_{ij}} + 1 \right) \cdot K_l \cdot t_{pt\_ij}}{S_{ct\_ij} \cdot z_{ij}}$$

and P_w – the market price of the workpiece, [uah]; P_{ct_ij} – the price of cutting tools set for machining the i-th surface on the j-th machine, [uah]; m – the number of metal-cutting machines involved in machining the part, [pcs]; n_j – the number of processed surfaces of the part on the j-th machine, [pcs]; K_l – random tool loss factor (accepted 1.1); S_{ct_ij} – stability of the cutting tool kit for machining the i-th surface on the j-th machine, [min]; t_{pt_ij} – main machining time of the i-th surface on the j-th machine, min; z_{ij} – the number of faces of the multi-sided, disposable cutting tool insert, [pcs]; C_{c_ij} – accordingly, the cost of refurbishing or replacing the multi-sided insert of the cutting tool, [uah]; S_{w_j} – salaries of main and auxiliary workers with accruals on the j-th machine, [uah]; C_{e_j} – the cost of electricity used to process the part on the j-th machine, [uah]; N_{pct_j} – the norm of the piece-calculation time of machining the part on the j-th machine, [min]; C_F – the value of fixed costs per component, [uah].

When determining the production cost of a part using the method of partial cost-sharing, fixed costs are not taken into account, thus, the objective function for determining the value of the production cost of a part using the method of partial cost-sharing has the form (3):

$$C_{CS} = P_w + \sum_{j=1}^{m} \left(\sum_{i=1}^{p_j} b^* + S_{w\_j} + C_{e\_j} \right), \tag{3}$$

where

$$b^* = \frac{\left(P_{ct\_ij} + \frac{C_{C\_ij}}{z_{ij}} + 1\right) \cdot K_l \cdot t_{pt\_ij}}{S_{ct\_ij} \cdot z_{ij}}.$$

As a generalized economic criterion of machining optimality, annual reduced costs (R_c) are used, which, unlike the production cost, also consider the economic efficiency of capital investments (4):

$$R_c = P_P + E_{ci} \cdot I, \tag{4}$$

where P_p – the cost of machining the annual production program; I – capital investment; E_{ci} – normative coefficient of capital investment efficiency (5):

$$P_p = C_p \cdot N_P, \tag{5}$$

where C_p – the production cost of manufacturing parts, [uah]; N_p – annual production program for the production of parts, [pcs].

The disadvantage of the cost criterion and the reduced cost criterion is that they determine the optimal machining variant on the basis of minimizing the manufactured cost, while in a modern economy, the goal of enterprises is to maximize profits. In turn, the minimum prime cost of goods does not guarantee its competitiveness and profit necessary for the development of the enterprise.

Profit occupies a leading position in the hierarchy of goals of a manufacturing organization. As an economic goal, profit characterizes the financial result of the enterprise's entrepreneurial activity [31]. Profit is an indicator that most fully reflects production efficiency, labor productivity, cost level, product quality, etc. At the same time, profit affects the strengthening of commercial activity, manufacture intensification, and is a source for the enterprise's intercompany needs. At the expense of profit, financing is carried out for scientific, technical and socio-economic development. So, for example, 89% of American companies in various sectors of the economy put profit on the first place among the goals of their activity. Therefore, the main goal of each enterprise is to obtain the greatest possible profit.

The amount of profit depends on the market price of the product and its cost. Under market economy conditions, the price of a product is determined by market factors, the main ones being supply and demand, and does not depend on the technological features of the manufacture of parts. Therefore, the cost remains the main factor that depends on part machining and affects the amount of an enterprise's profit.

Changes in tax, customs, and other government policies affect the price, cost, and profit of enterprises. In these circumstances, in an unstable economic and socio-political situation, the most significant financial goal of an enterprise is to maximize profits in the shortest possible time. The criterion of "intensity of marginal profit" (I_{mp}, [uah/min]), which reflects the amount of received marginal income from the sale of products per unit of time spent on their production, is fully in line with this objective.

The objective function for determining the intensity of marginal profit, that is, when determining the cost of a part using the method of partial cost-sharing, has the form (6), where P_d – market price of the part.

The objective function for determining the intensity of profit when calculating the cost of a part using the method of complete cost allocation has the form (7).

Therefore, the calculation of the amount of profit and marginal income is performed according to the following relationships (8)–(9)

$$I_{mp} = \frac{P_d - P_w}{\sum\limits_{j=1}^{m} N_{pct\_j}} - \frac{\sum\limits_{j=1}^{m} c^*}{\sum\limits_{j=1}^{m} N_{pct\_j}}, \tag{6}$$

$$I_p = \frac{P_d - P_w}{\sum\limits_{j=1}^{m} N_{pct\_j}} \frac{\left(\sum\limits_{j=1}^{m} c^* + C_F\right)}{\sum\limits_{j=1}^{m} N_{pct\_j}}. \tag{7}$$

$$\Pi = P_d - P_w - \left(\sum_{j=1}^{m} c^* + C_F\right), \tag{8}$$

$$\Pi_M = P_d - P_w - \sum_{j=1}^{m} c^*, \tag{9}$$

where

$$c^* = \left(\sum_{i=1}^{p_j} \frac{(P_{ct\_ij} + \frac{C_{C\_ij}}{z_{ij}} + 1)\cdot K_l \cdot t_{pt\_ij}}{S_{ct\_ij}\cdot z_{ij}} + S_{w\_j} + C_{e\_j}\right).$$

Results

For the formed variants of machining of a prismatic workpiece (Fig. 1), Figs 2–4 show a comparative analysis of the considered technical and economic criteria, depending on the size of the production batch of parts. Thus, the previously described variants of the technological processes of part machining in accordance with Table 1 (1, 2, 3, 4) were presented in Figs 2–4.

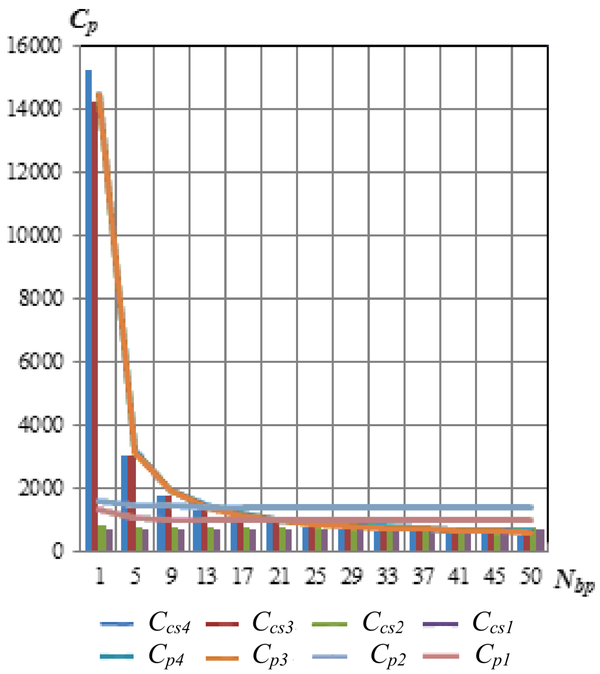

Fig. 2. Dependences of the machining cost on the size of the production batch of parts: 1, 2, 3, 4 – variants of machining the parts in accordance with Table 1.

Please note that both methods and the calculation of the machining cost by the method of full cost allocation and the calculation of the cost of machining by the method of partial cost distribution are presented in the figures.

As can be seen from the graphs, the use of the profit criterion as a technical and economic criterion allows to reduce the value of the critical program of run-out production for cases of machining a part on CNC machines in comparison with the cost of machining, and the use of the profit intensity criterion further reduces this value.

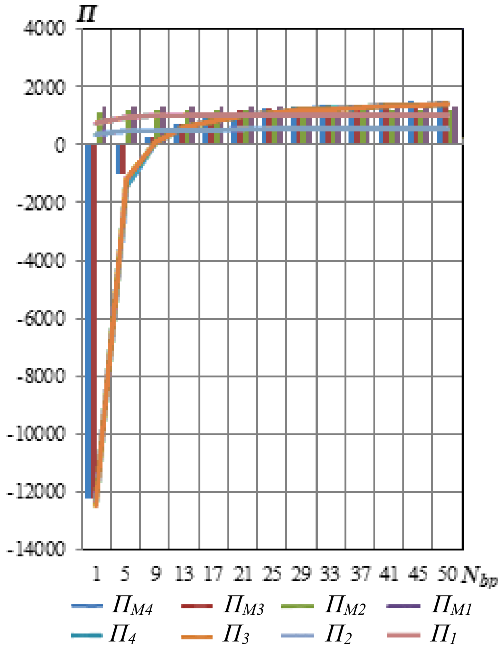

Fig. 3. Dependences of profit on the size of the production batch of parts: 1, 2, 3, 4 – variants of machining the parts in accordance with Table 1

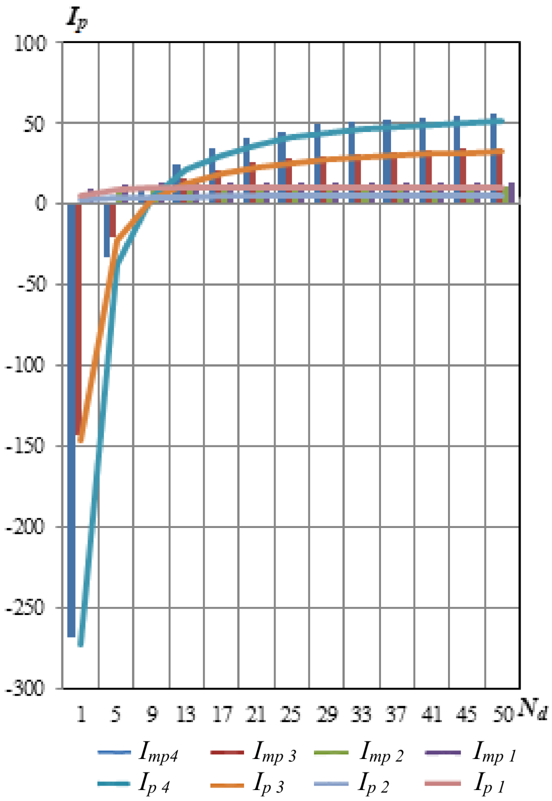

Fig. 4. Dependences of the intensity of profit on the size of the production batch of parts: 1, 2, 3, 4 – options of machining the part in accordance with Table 1.

Table 2
The results of determining the optimal machining variant.

Criteria combination variant	Optimality criteria	Machining variant		
		The value of the production batch of parts, [pcs]		
		No 1	No 2	No 3
1	The intensity of shaping and the cost of manufacturing, determined by the method of complete cost allocation	1–12	13–24	25–1000
2	The intensity of shaping and the cost of manufacturing, determined by the method of partial cost-sharing	1–34	35–42	43–1000
3	The intensity of shaping and profit Intensity	1–11	12–19	21–1000
4	The intensity of shaping and intensity of marginal profit	1–8	9–13	14–1000

So, for example, the cost of manufacturing a part on CNC machines will be the smallest when the size of the production batch is more than 50 parts (Fig. 2), and the greatest profit can be obtained with the size of the production batch of 27 parts (Fig. 3), while the maximum profit intensity will be observed already with 19 parts in the production batch (Fig. 4).

It should also be noted that with such a production batch of parts, the criterion of profit intensity allows, from an economic point of view, to machine workpieces on CNC machines which were obtained by various casting methods, while the maximum income would be achieved when the workpieces were manufactured from rolled steel. Thus, the use of the criterion of profit intensity makes it possible to extend the boundaries of the effective use of CNC machines and workpieces obtained by various casting methods.

The choice of the optimal machining that considers several indicators is carried out by multi-criteria optimization. The need for multi-criteria optimization of the machining is due to the fact that individual criteria cannot be reduced to each other and they are in a complex relationship with each other, which, in turn, is characterized by their inconsistency [32].

For the considered variants of machining in manufacturing a prismatic workpiece (Table 1), multicriteria optimization of the machining was carried out by the method of weighting coefficients using various optimality criteria. The results of the investigation are given in the Table 2.

Determining the cost by the method of partial cost-sharing allows extending the scope of the effective use of both CNC machines and manual control machines.

Conclusions

It is advisable to determine the optimal part machining based on multicriteria optimization using the criteria that reflect the technological and economic aspects of the manufacturing enterprise.

Calculation of the cost of part machining by the method of partial cost-sharing allows increasing the volume of the production batch by 2.83 times. In this case, it was proved that rolled steel is economically viable under the conditions of machining on machines with manual control (option No. 1), and that machining on CNC machines allows increasing the volume of the production batch by 1.75 times (option No. 3).

Using the intensity of marginal profit as a criterion of optimality in comparison with the cost of machining makes it possible to extend the scope of the efficient use of CNC machines.

Whereas when using the intensity of marginal profit criterion, the production batch of parts, for which the use of CNC machines is economically profitable, decreases on average by 2.6 times for workpieces from rolled steel products and by 2.28 times for workpieces from molding.

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