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Methods of Efficient Use of Cnc Machines and Resource Saving in Part Processing

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Annotation
This article discusses methods of efficient use of computer numerical control (CNC) machines in part processing. The study highlights resource-saving technological solutions, optimization of cutting modes, and strategies for extending tool life. Practical recommendations are also proposed to improve production efficiency and reduce energy consumption.

Keywords: CNC machines, part processing, resource saving, efficiency, technological solutions.

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INTRODUCTION

In modern mechanical engineering, the use of Computer Numerical Control (CNC) machines has become one of the main directions of the production process. CNC machines make it possible to manufacture parts with high precision and in a short time. At the same time, the issues of resource saving and increasing efficiency in production are considered highly relevant. To achieve this, it is necessary to properly organize technological processes, introduce advanced machining methods, and use tools efficiently.

It has been proven that the tooling costs of operations often dominate the overall cost balance associated with performing those operations. This determined the main idea of the developed methodology for creating resource-saving operations: to minimize the number of tools used by rationally forming the structure of operations through tooling transitions that ensure the processing of surface complexes using a single tool.

To reduce the tooling costs of operations, the main task is to determine the optimal number of simple transitions combined in the operations performed on the machine, as well as to rationally define the degree of concentration of these tooling transitions. The first of these levels mainly determines the structure of the route technological process for part manufacturing [1], while the second determines the structure of the operation performed on the machine.

METHODS

Single and small-batch production types correspond to highly concentrated operations. The inclusion of such operations in the route technological process must be economically justified.

1) When determining the appropriate number of simple technological transitions combined in the operations performed on the machine, the following rules are taken into account:
2) The part setup scheme in the operation performed on the machine is known;
3) The quality of the technological bases corresponds to the selected setup scheme [2];
4) The surfaces of the part that can be reprocessed during the machine operation exist in accordance with the selected setup scheme;

The capacity of the machine tool magazine is sufficient to accommodate the selected tools.

The degree of concentration of simple transitions in a machine operation is determined based on the given criteria if the operation — which ensures a certain required quality of part production — corresponds more closely to the technological capabilities of the machine compared to a set of technological operations that it replaces, even when performed on machines with more limited technological capabilities.

Let us assume that, for the production of a part, a route technological process "A" has been developed, which previously included *i* technological operations. The total costs required to implement it are as follows:

$$X_A = \sum_{i=1}^{i=I} X_i, \quad (1)$$

here X_i — The costs allocated for performing the *i-th* operation of the route technological process "A", $i = 1, \dots, L$

$$X_i = C_i + E \cdot K_i, \quad (2)$$

here C_i — The cost for the *i-th* operation (the variable part of the current expenses);

K_i — The capital investments required for performing the *i-th* operation; E — the coefficient of relative efficiency of investments [3]. By selecting certain *L* operations in the route process "A", the following can be written:

$$X_A = \sum_{i=1}^{i=L-1} X_i + X_L + \sum_{i=L+1}^{i=I} X_i, \quad (3)$$

When operation **L** is performed on the machine, it allows not only its own execution but also the implementation of all subsequent operations **i = L+1,…, I** in a single (L) working cycle. The technological process route **"A"** is thus transformed into another route — **"B"**, and the cost of implementing it ($\mathbf{X_B}$) can be determined using the following formula:

$$X_B = \sum_{i=1}^{i=L-1} X_i + X_{LB}, \quad (4)$$

here X_{LB} — The cost of performing operation **L** in the **"B"** process route. In this cas

$$X_{LB} = k \cdot X_L, \quad (5)$$

here $k > 1$ – The cost increase coefficient for performing the concentrated **L** operation in the **"B"** process route. The change in current expenses (**ΔX**) associated with converting the **"A"** process route into the **"B"** route.:

$$(\Delta X = X_A - X_B = X_L + \sum_{i=L+1}^{i=I} X_i - X_{LB} = X_L + \sum_{i=L+1}^{i=I} X_i - k \cdot X_L, \quad (6)$$

This is appropriate for this purpose.:

$$(\Delta X > 0. \quad (7)$$

"Taking (6) into account and, after rearranging (4.7), we obtain"

$$\frac{\sum_{i=L+1}^{i=I} X_i}{X_L} > (k-1), \quad (8)$$

The above inequality (8) determines the economic efficiency of the concentrated operation performed on CNC machines and the rationality of the structure of the “B” route technological process.

At the same time, due to the general methodological approach to evaluating the feasibility of switching to route processes—including concentrated operations performed on CNC machines—the inequality (8) is specific, as it characterizes the costly aspect of constructing and implementing the route process synthesis and its structure.

If the latter is organized differently or if other efficiency criteria are applied, the conditions corresponding to (8) will also differ. For example, when manufacturing body parts using CNC machines, there exist several options for constructing route technological process structures, such as:

$$\begin{aligned} &а)\ O_l, O_{MC1}; \\ &б)\ O_l, O_{MC1}, O_2, \dots, O_n; \\ &в)\ O_l, \dots, O_k, O_{MC1}, O_{k+1}, \dots, O_n; \\ &г)\ O_l, \dots, O_k, O_{MC1}, \{O_{k+1}, \dots, O_l, O_{MC2}, O_{l+1}, \dots, O_n\}; \end{aligned} \quad (9)$$

Here, $O_l,\dots,O_n$ are operations performed on manually operated machines or CNC machines with machining capability; O_{MC1} are operations performed on the machining center.

The structure (9,a) ensures the maximum concentration of technological transitions in the operations performed on the machining center. The O_l operation only provides reprocessing of the technological bases of the workpiece. The degree of transition concentration in the machining center operation (9,b) is lower than in (9,a). The O_l operation ensures the preparation of technological bases, while operations $O_2,\dots,O_n$ involve finishing and final machining of the part, which for various reasons cannot or should not be performed on the machining center. The structure (9,c) differs from the previous one only in the number of rough or semi-finish machining operations. The structure (9,d) is similar to the previous one but provides for the use of several machining centers in production. Usually, the number of machining centers used is determined by the technological complexity of the manufactured part and does not exceed 3–5. For such structures, the degree of transition concentration in machining center operations (9,d) can vary from a high level corresponding to conventional CNC machine operations to the maximum achievable concentration level.

The task of synthesizing the primary structure of the route technology in the proposed work does not consider the application of the methodology during the manufacturing process of the part [5].

A methodology has been developed for forming the composition of machining center (MC) operations with maximum concentration of technological transitions (9,a)…(9,d):

1. **Divide** the machining of the part into T-complexes and determine quality requirements for them (Table 1).
2. **Preliminarily form** the structure of the route technological process for manufacturing the body part using CNC machines.
3. **Determine** the complete set of technological transitions required for part manufacturing.
4. **Distribute** technological transitions preliminarily between operations. CNC operations include: a) transitions for machining surfaces (T-complexes) that can only be performed on CNC machines; b) transitions for machining T-complexes that, due to positional accuracy requirements, are recommended to be performed in a single setup.
5. **Define** the content of the first operation (O_1) of the process (machining of reference surfaces for CNC operations). Choose the setup scheme and rough referencing.
6. **If** one operation (O_1) is not sufficient to prepare the technological bases for CNC machining, form the necessary operations (O_1...O_k), including not only transitions for machining reference surfaces but also other transitions that must be performed on equipment of the selected type according to the setup scheme.
7. **Select** all available T-complexes that can be machined on CNC equipment according to the chosen setup scheme.
8. **Identify** T-complexes that can, in principle, be machined on a CNC machine using the selected setup scheme.
9. **Form** the composition of CNC operations by listing the transitions for machining T-complexes according to item 7, including transitions that are advisable to perform together with those defined in item 3.

RESULTS

An example of implementing the method in the manufacturing of a test body part is presented (Figure 1). The blank material is **steel 40 (GOST 1050-88).**

The division of the part into reprocessed **T-complexes** is shown in Figure 1. The structure of the part model consists of a set of T-complexes (Table 1): {TK11, … ,TK18; TK31, TK32, TK33; TK151, … , TK153; TK51, TK52; TK12}.

Technological processes for manufacturing the body part are developed based on different route structure variants (Table 2). In the presented variants, the main machining volume of the part is performed on a CNC machine with a horizontal spindle equipped with a rotary table (operation 010). The blank is positioned by two Ø12H7 holes with parallel axes (TK121, TK123) and the plane TK11, which is perpendicular to them.

The concentration of transitions in operation 010 decreases due to the impossibility of machining T-complexes TK31 and TK32, since one of their surfaces is used for fixing the part, blocking tool access.

In this operation, the transition concentration can be maintained by machining T-complex TK14 using end milling instead of finger milling.

The feasibility of implementing one of the proposed route variants for part manufacturing can be evaluated by comparing production productivity for different operations — (020, 025 for variant 1) and (020 for variant 2).

Ensuring productivity in constructing technological operations on CNC machines is primarily achieved through the rational design of tooling transitions developed with original technical solutions (Figure 2).

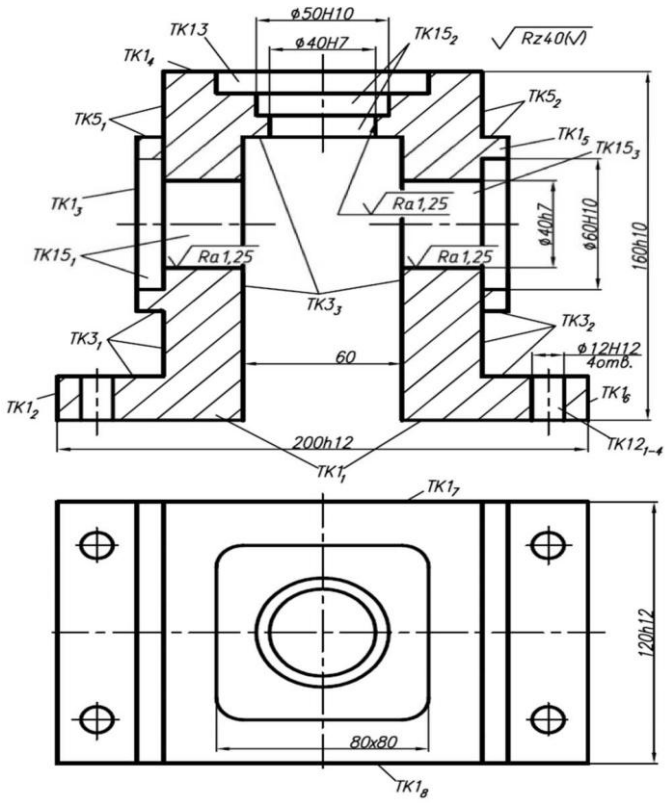

Figure 1. Test sketch of the body part

Table 1. Some test variants of route technological process structures for manufacturing the body part

№	Operation number and content	Machined T-complex	Transition duration
1	**005 CNC Vertical Milling**	$TK1_1$	Face milling;
		$TK12_{1-4}$	Drilling; Reaming;
		$TK3_3$	End milling;
	010 Multi-purpose CNC	ТКУ ТК1з; ТК15; $TK1_6$;	Face milling;
		$TK5_1$; $TK5_2$	End milling;
		$TK15_1$; $TK15_3$	Drilling; Hole boring;
	015 Horizontal Milling	$TK3_1$; $TK3_2$	End milling;
	020 CNC Vertical Milling	TK13	End milling;
		TK152	End milling;
	025 Coordinate Boring	TK152	Drilling; Hole boring; Boring and reaming;
2	**Variant 1:** 005, 010, 015	Variant 1	Variant 1
	020 Multi-purpose CNC	$TK1_4$	Face milling;
		TK13	End milling;
		TK152	Drilling; Hole boring;

The source for constructing operations is the model of the workpiece to be machined on the machining center (MC). The model unites the following:

a) surfaces of the workpiece that can be used as setup bases for MC operations, as well as surfaces that are not technologically affected during the MC operation;

b) surfaces machined during MC operations;

c) surfaces to be machined in subsequent operations;

d) surfaces that are essentially not machined.

Dividing the part into T-complexes is performed only for surfaces that are machined, using the T-complex catalog (Table 1). If the permitted size of a complex with a given accuracy cannot be achieved in a single pass, the complex's machining is developed as a sequence of elementary technological passes. Using the "Tool" database and the "machining method" command, the full set of tool types and their parameters required for machining each T-complex is formed. Each T-complex included in the model corresponds to many types of tools required for its manufacture. For each tool type, numerous parameters are identified that allow selecting its specific variant. The set of T-complexes is divided into small groups according to the characteristics of tool types used for their production and, accordingly, the conditions for manufacturing with a common tool. T-complexes that do not match the production conditions with the common tool are separated. For each complex that is part of the selected small sets, the economic feasibility of machining is determined by the common tool and others [8].

Evaluate the expected machining accuracy; if necessary, adjust the machining regime or decide to compensate for tool wear to achieve the specified accuracy. For each T-complex's machining process, form variants of tool usage taking into account the nominal life of the tool [8] and variations in cutting mode during tool passes. An example of implementing the developed methodology in a simplified form is considered for the manufacturing of the test part — operation 010 from Table 1 (Table 5.1) (Figure 5.1). The indicated operation can be constructed from elementary technological passes, each performed on a machining center (MC) with a horizontal spindle using its own cutting tool (Table 5.2). The operation can consist of a combination of simple and tooling technological passes that differ in the tools used and the T-complexes they machine (Tables 3 and 4). Table 5 presents the results of the technical and economic evaluation

Table 2. ***Composition and machining parameters of operation 010 constructed from simple technological transitions***

Transition No.	Type	Machined Complex	Cutting Tool	B, mm	Tool Life				T, min	L, mm	t_0, min
					t, mm	S_{01}, mm/rev	V, m/min	n, rev/min			
1(8)	O	TK15	Face milling Ø100, z=10, T15K6	80	2	0,6	251	800	224	120	0,25
2(9)	O	TK16	Face milling Ø100, z=10, T15K6	20	2	0,6	251	800	295	120	0,25
3(10)	O	$TK5_2$	End milling Ø50, z=8, VK8	10	30	0,06	125	800	196	120	2,5
4(11)	O	$TK15_3$	Drilling Ø25	-	12,5	0,3	19,6	250	56	40	0,53
5(12)	O	$TK15_3$	Drilling Ø37	-	6	0,5	29	250	78	40	0,32
6(13)	O	$TK15_3$	Boring tool	-	1,3	0,24	146,8	1250	80	30	0,5
7(14)	O	$TK15_3$	Boring tool	-	0,2	0,1	157	1250	100	30	0,24
15	O	$TK1_7$	Face milling Ø100, z=10, T15K6	160	2	0,5	251	500	246	200	0,8
16	O	TK18	Face milling Ø100, z=10, T15K6	160	2	0,5	251	500	246	200	0,8

Note: O – simple transition; B – milling width; t – cutting depth; S_0 – feed per revolution; V – cutting speed; n – spindle speed; T – tool life; L – machining length; t_0 – main machining time

Table 5. ***Some technical and economic indicators of operation 010 variants***

Operation construction / variant	P_0, pcs	$M(l_0)$, pcs	k_{iu},	b, pcs	$t_п$, min
Simple transitions	16	16	1	78	18.2
Simple and toolmaking transitions (Variant 1)	16	12	1.33	78	21.8
Simple and toolmaking transitions (Variant 2)	16	10	1.6	5	27.3
Note: P_0 – number of simple transitions in the operation; $M(l_0)$ – capacity of the tool set used in the operation; k_{iu} – cutting tool intensity factor; b – minimum number of workpieces processed during the tool's service life; t_d – unit (per-piece) time; Q – productivity.					

DISCUSSION

Undoubtedly, the operation constructed according to variant 2, which consists of simple and instrumental technological transitions, cannot be accepted due to the insufficient number of workpieces processed during the tool's durability period. The increase in the main time during the 11th transition (Table 20) is explained by the longer trajectory of the relative movement of the tool and its relatively low durability when processing the TK17 and TK18 complexes.

Despite the inevitable increase in working time, constructing the operation according to variant 1 is more optimal (Table 21).

A comparison of the relative values of the technical and economic indicators of operations composed of simple transitions and those consisting of simple and instrumental transitions (variant 1) was carried out.

The "useful effect" criterion (K_on) was evaluated using the following formula:

$$K_{on} = \frac{1}{t_д \cdot Q} \qquad (10)$$

The obtained data reliably confirm the prospects of using the developed methodology for constructing operations that increase productivity in the manufacturing of body parts on machining centers (Fig. 3).

The resource-saving operation design methodology was tested under production conditions for machining complex-shaped body parts, including those with hard-to-reach and high-precision surfaces, on machining centers: Hermle C1200 (rough machining), Mikron UCP800 Duro (semi-finishing), and Hermle C40 (finishing). The accuracy of the main surfaces was within IT6…IT8, with form and positional tolerances of 0.005…0.01 mm. The developed methodology was applied to ensure dimensional accuracy of diametrical surfaces.

In production, the workpieces of body parts were machined using tools equipped with replaceable metal-ceramic (including carbide) inserts from various manufacturers, made according to different standards (Appendix, Section 2). When constructing operations, efforts were focused on reducing tool consumption by increasing the intensity of tool utilization and lowering tool cost compared to conventional production preparation methods. When determining the tool cost (X), expenses for insert holders, cutter bodies, or non-replaceable cutter components were not considered. The economic accuracy of the saved material volume was taken into account during tool selection.

Table 6. Economic accuracy achieved in machining center (MC) operations using certain tools

Cutting tool name	Accuracy grade (IT)	Cutting part	Number of inserts
Face mill	Up to IT8	Replaceable inserts (RI)	4...6
End mill	Up to IT8	RI	2...4
Twist drill	Up to IT10	RI	2
	IT10…IT7	Brazed insert	-
	Up to IT6	Solid carbide	-
Reamer	IT6, IT7	Solid carbide	-
Boring head	IT6, IT7	RI	1
Boring head	IT8, IT9	RI	3

Machining center (MC) productivity improvement methodology industrial testing results showed that:

1. **Traditional process preparation and operation planning methods** retain unused potential to reduce machining costs due to insufficient concentration of technological transitions and excessive use of tools.
2. **The developed methodology** for constructing productivity-oriented operations in machining centers allows cost reduction by rationally intensifying tool and equipment use, ensuring stable production of quality parts in small and medium-scale manufacturing.
3. **Increasing the coefficient of tool-equipment utilization intensity** leads to a proportional average reduction in tooling costs compared to traditional process preparation methods.
4. **It has been proven** that when machining body parts made of aluminum alloys and structural alloy steels on multi-purpose CNC machines, tooling costs for roughing and finishing operations can be reduced by **1.2–1.4 times.**

CONCLUSION

1. Traditional methods of process preparation and operation planning retain unused potential for reducing production costs due to insufficient concentration of technological transitions and excessive use of cutting tools.
2. The developed methodology for constructing productivity-oriented operations in machining centers allows reducing implementation costs by rationally intensifying the use of tools and equipment, ensuring stable production of quality parts in small- and medium-scale manufacturing.
3. An increase in the coefficient of tool and equipment utilization intensity leads to a proportional average reduction in tooling costs compared to traditional process preparation methods.
4. It has been proven that when manufacturing body parts made of aluminum alloys and structural alloy steels on multi-purpose CNC machines, tooling costs for roughing and finishing operations can be reduced by **1.2–1.4 times.**

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