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THE MODEL FOR OPTIMIZING CUTTING PARAMETERS FOR PRO-
CESSING PRODUCTS ON METAL-CUTTING MACHINES

Irina Khrustaleva
Higher School of Mechanical engineering
Institute of Machinery,
Materials and Transport
Peter the Great St.Petersburg
Polytechnic University (SPbPU)
Russia
Irina.khrustaleva@mail.ru

Michail Khrustalev
Higher School of Mechanical engineering
Institute of Machinery,
Materials and Transport
Peter the Great St.Petersburg
Polytechnic University (SPbPU)
Russia
m320prk1@rambler.ru

Yana Brovkina
Higher School of Mechanical engineering
Institute of Machinery,
Materials and Transport
Peter the Great St.Petersburg
Polytechnic University (SPbPU)
Russia
zoom87@list.ru

Vladimir Khokhlovskiy
Higher School of Cyber-Physical Systems Management
Institute of Computer Science and Cybersecurity
Peter the Great St.Petersburg
Polytechnic University (SPbPU)
Russia
I78v.kh77@gmail.com

Vyacheslav Shkodyrev
Higher School of Cyber-Physical Systems Management
Institute of Computer Science and Cybersecurity
Peter the Great St.Petersburg
Polytechnic University (SPbPU)
Russia
shkodyrev@mail.ru

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Abstract

The paper discusses the issues of multi-criteria optimization of the process of manufacturing products on metal-cutting machines. The efficiency of the optimization process directly depends on its level of detail and the optimal set of targets and control parameters. The change in the structure and properties of a product during its manufacture can be represent-ed in the form of a hierarchical model based on the decomposition of the original goal, which must be achieved through the comprehensive optimization of individual elements of the process. Described herein is a multi-level hierarchical model for optimizing a ma-chining process comprising five levels of control. The following control levels are identified: Technological Process, Processing Stage, Technological Operation, Process Transition, Work Stroke. For each structural element of the model, control parameters, specific optimization criteria are defined, and vector optimiza-tion criteria are formed. The practical implementation of the control model is presented on the example of optimization of the target indicators of the technologi-cal process of the "Roller" product. Graph of change of object states in process of its manufacturing is pre-sented, optimal values of target indicators and cutting parameters are determined.

Key words

multicriteria optimization, technologi-cal process, vector optimization criteria, hierarchical model, machining.

1 Introduction

Increasing competition and rapid pace of devel-opment of production contribute to the widespread introduction of digital technologies at all stages of the production process. In the market economy, taking into account the growing level of competition among industrial enterprises, the introduction of digital tech-nologies into the production process is one of the key conditions for increasing the efficiency of the enter-prise's economic activity. The creation of a multi-level model of the production process allows to optimize the parameters of the production flows of the enterprise based on multi-criteria analysis.

Currently, the issues of multi-criteria optimi-zation and the introduction of digital technologies into the production process are one of the most pressing tasks in the field of mechanical engineering, which is confirmed by numerous publications in the scientific literature [Vuković et al., 2024; Dogan and Birant, 2021; Adane et al., 2019;

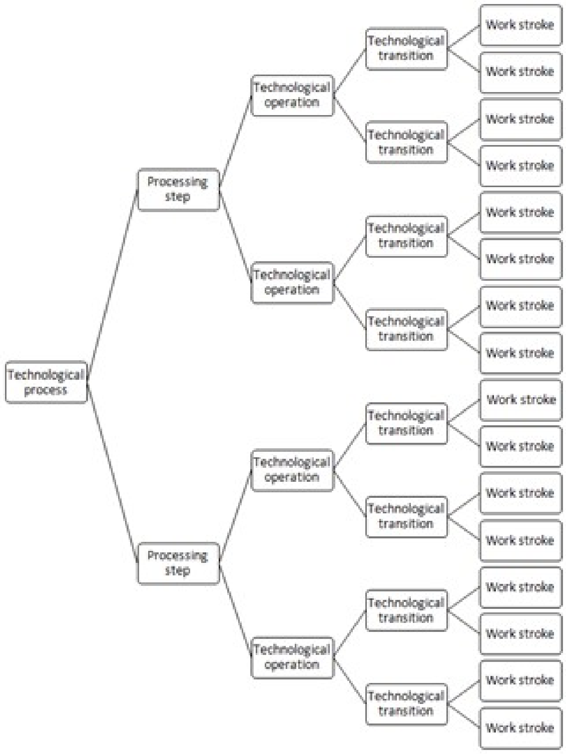

Figure 1. Structural model of the technological process of manufacturing the product on metal-cutting machines

Gashi et al., 2021; Georgiadis and Michaloudis, 2012; Li et al., 2021; Li and Yang, 2021; Khrustaleva et al., 2021; Li et al., 2022].

The solution of the problem of multi-criteria optimization of production processes is based on the analysis of a large amount of information and cannot be effectively solved without the use of artificial intel-ligence and Big Data technologies [Zhang et al., 2020; Guo et al., 2020; Shah et al., 2020; Garcia-Planas, 2023].

Optimization methods based on knowledge graphs [Li and Chen, 2024; Xu et al., 2024b; Hao et al., 2021; Melnikov and Terentyeva, 2023; Erofeeva and Parsegov, 2024; Qin et al., 2023; Yadav et al., 2021], which are a semantic network describ-ing the structure of an object and the relationships between its individual elements, are widespread.

One of the key performance indicators of the enterprise is the quality of products. To optimize this target indicator, the Taguchi method is used [Rajaravi and Gobalakrishnan, 2023; Saravanan et al., 2023; Selvarajan et al., 2023b], which makes it possible to assess the quality indicators of the manufactured products and the losses that oc-cur as the values of the technical parameter of the product deviate from the nominal, including within the tolerance.

The scientific literature presents models for solving production problems based on the Pareto op-timization method, which makes it possible to find a system state in which the value of each particular in-dicator characterizing the system cannot be improved without worsening the others [Xu et al., 2024a; Ming et al., 2024; Selvarajan et al., 2023a; Zhou et al., 2023; Feng et al., 2021; Kostenko et al., 2021; Kostenko et al., 2020].

Within this work, issues of optimizing the pa-rameters of the technological process of manufactur-ing products on metal-cutting machines are consid-ered.

The purpose of the work is to develop a hier-archical model of multi-criteria optimization of the parameters of the technological process of manufac-turing parts on metal-cutting machines.

The objective of the study is a structural analysis of the process of manufacturing products on metal-cutting machines; identification of factors af-fecting the efficiency of the product manufacturing process on metal-cutting machines; generating a plu-rality of process targets and control parameters.

A model for optimizing the parameters of the manufacturing process of parts. The process of manufacturing a detail on metal-cutting machines is accompanied by a change in the structure and proper-ties of the workpiece as a result of the implementation of an appropriate set of sequential actions. This pro-cess as a control object can be described in the form of a structurally complex model, which is based on the structural model of the technological process (Figure 1).

The result of the decomposition of the control object is a five-level structural model containing the following control levels (Figure 2):

1. Technological process.
2. Processing step.
3. Technological operation.
4. Technological transition.
5. Work stroke.

The first level of control describes the state of the product at the technological process level. In this case, the object product has two states: S_wp – the state of the product before the implementation of the technological process and S_pr – the state of the product after the completion of the technological process (Figure 3). The Arc E_{wp-pr} describes the conditions for the transition of an object from the S_{wp} state to the S_{pr} state.

The transition condition of the object from the S_{wp} state to the S_{pr} state can be described by the following expression (1):

$$S_{pr} = f(S_{wp}, U1),\ U_1 \subset D, \qquad (1)$$

$$\begin{aligned} U_1 = \{& N^{\Pr St}, (Type_{ShM}^{Tech\,\Pr})_n, \beta_{bas}^{Tech\,\Pr}, \beta_{aux}^{Tech\,\Pr}, \\ & \alpha_{ct}^{Tech\,\Pr}, \alpha_{w}^{Tech\,\Pr}, \alpha_{qwq}^{Tech\,\Pr}, \alpha_{am}^{Tech\,\Pr}, \alpha_{rep}^{Tech\,\Pr}, \\ & \alpha_{el.en.}^{Tech\,\Pr}, \alpha_{dif}^{Tech\,\Pr}, (\gamma_i^{gee})_n\}, \end{aligned} \qquad (2)$$

where U_1 — the vector of control parameters at the first control level; $N^{\Pr St}$ — the number of processing steps within the technological process, pcs.; $(Type_{ShM}^{PrSt})_n$ —

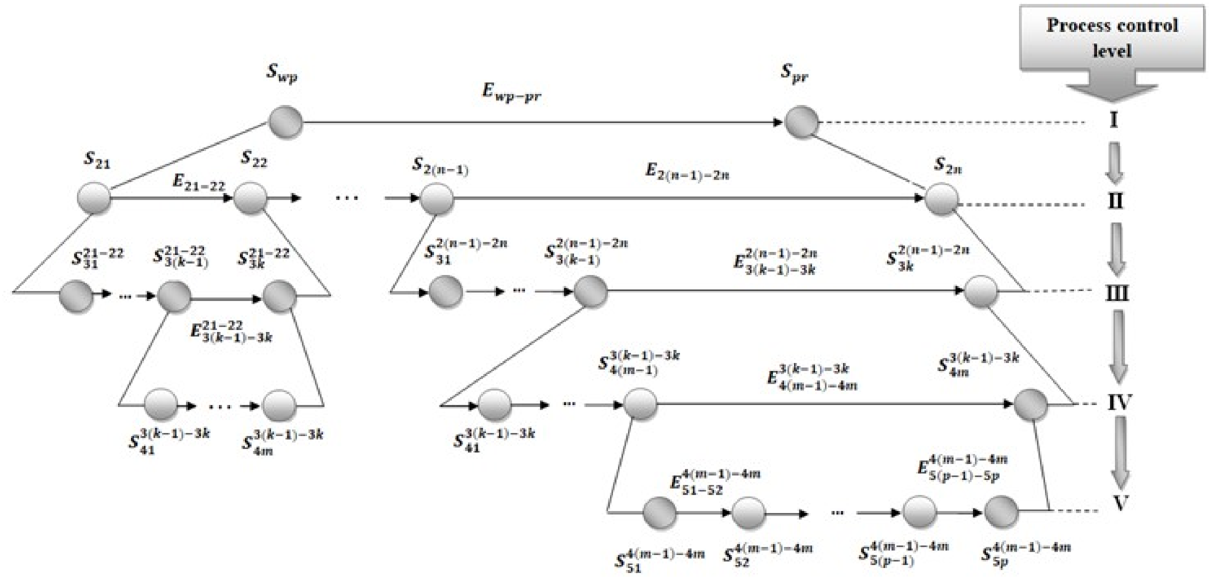

Figure 2. Structural model of the technological process of manufacturing the product on metal-cutting machines

a processing method used within the n-th processing step; $\beta_{bas}^{TechPr}, \beta_{aux}^{TechPr}$ — the share of the time dedicated to the implementation of complexes of basic and auxiliary actions in the total labor intensity of the technological process; $\alpha_{ct}^{Tech\,\mathrm{Pr}}$, $\alpha_{w}^{Tech\,\mathrm{Pr}}$, $\alpha_{qwq}^{Tech\,\mathrm{Pr}}$, $\alpha_{am}^{Tech\,\mathrm{Pr}}$, $\alpha_{rep}^{Tech\,\mathrm{Pr}}$, $\alpha_{el.en.}^{Tech\,\mathrm{Pr}}$, $\alpha_{dif}^{Tech\,\mathrm{Pr}}$ — the shares of costs intended for the purchase of cutting tools and quick-wear equipment, payment of wages to production workers, amortization, maintenance and repair of technological equipment, payment of electricity and other costs, respectively, in the total cost of implementing the technological process; $(\gamma_i^{gee})_n$ — the share of the error for the i-th geometric parameter at the m-th processing stage caused by the geometric error of the technological equipment from the tolerance field for the corresponding parameter; D — the multiple optimization model control parameters.

At the first control level, three groups of targets are defined:

The first group of the targets that characterizes the accuracy of the geometric parameters of individual detail elements within the technological process — Tr_{11}^{TechPr}.

The second group of the target indicators characterizing the values of capital investments and operating costs within the technological process — Tr_{12}^{TechPr}.

The third group of the target indicators, which characterizes the duration of the sets of basic and auxiliary actions within the technological process — Tr_{13}^{TechPr}.

The groups of the target indicators Tr_{11}^{TechPr}, Tr_{12}^{TechPr}, Tr_{13}^{TechPr} have the following structure (3)-(6):

$$Tr_{11}^{TechPr} = \{AcIn_1^{\mathrm{Pr}\,St}, \ldots AcIn_n^{\mathrm{Pr}\,St}, (Err_1)_1, \ldots, (Err_j)_n\}, \quad (3)$$

$$Tr_{12}^{TechPr} = \{CAPEX^{Tech\,\mathrm{Pr}}, OPEX^{Tech\,\mathrm{Pr}}\}, \quad (4)$$

$$Tr_{13}^{TechPr} = \{T_{bas}^{Tech\,\mathrm{Pr}}, T_{aux}^{Tech\,\mathrm{Pr}}\}, \quad (5)$$

$$Tr_{11}^{TechPr} \subset Tr^{TechPr},\ Tr_{12}^{TechPr} \subset Tr^{TechPr},\ Tr_{13}^{TechPr} \subset Tr^{TechPr}, \quad (6)$$

where Tr^{TechPr} — the multiple individual optimization criteria for the first control level; $AcIn_m^{\mathrm{Pr}\,St}$ — the accuracy index of geometric parameters within the n-th processing stage; $(Err_j)_n$ — the error value caused by geometric inaccuracy of process equipment, as a result of the use of the j-th unit of process equipment within the n-th processing stage, $\mu m.$; $CAPEX^{Tech\,\mathrm{Pr}}$ — the amount of the capital investments for the implementation of the technological process, rubles; $OPEX^{Tech\,\mathrm{Pr}}$ — the amount of operating costs for the implementation of the technological process, rubles; $T_{bas}^{Tech\,\mathrm{Pr}}$ — the labor intensity of performing a set of basic actions within the technological process, min; $T_{aux}^{Tech\,\mathrm{Pr}}$ — the labor intensity of performing a set of auxiliary actions within the technological process, min.

Thus, the vector optimization criterion for the first control level can be written as follows (7):

$$\begin{gathered} F^{TechP}(U_1) = \\ = (AcIn_n^{\mathrm{Pr}\,St}(U_1), (Err_j)_n(U_1), \\ CAPEX^{Tech\,\mathrm{Pr}}(U_1), OPEX^{Tech\,\mathrm{Pr}}(U_1), \\ T_{bas}^{Tech\,\mathrm{Pr}}(U_1), T_{aux}^{Tech\,\mathrm{Pr}}(U_1)) \end{gathered} \quad (7)$$

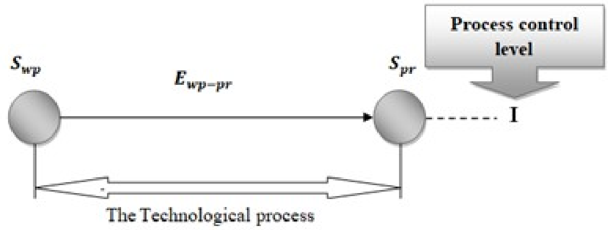

Figure 3. The graph of the first control level

The second control level describes the state of the object within the processing stage (Figure 4). In this case, the control object within the processing step can be represented as the following sequence of intermediate states (8):

$$S_{wp} \to S_{21} \to S_{22} \to \cdots \to S_{2(n-1)} \to S_{2n} \to S_{pr}, \tag{8}$$

where $S_{21}, S_{22}, S_{2(n-1)}, S_{2n}$ — the 1st... n-th intermediate state of the object within the second control level; n — the number of intermediate object states in the second control level.

The condition of transition of the control object from the state S_{n-1} to the state S_n can be described by the following expression (9):

$$\begin{gathered} S_{2n} = f(S_{2(n-1)}, U_2), \\ U_2 = \{N_n^{TechOp}, (\beta_{bas}^{\Pr St})_n, (\beta_{aux}^{\Pr St})_n, \\ (\alpha_{ct}^{\Pr St})_n, (\alpha_{w}^{\Pr St})_n, (\alpha_{qwq}^{\Pr St})_n, \\ (\alpha_{am}^{\Pr St})_n, (\alpha_{rep}^{\Pr St})_n, (\alpha_{el.en.}^{\Pr St})_n, (\alpha_{dif.}^{\Pr St})_n\}, \end{gathered} \tag{9}$$

where U_2 – the vector of control parameters at the second control level; N_n^{TechOp} — the number of process operations within the n-th processing stage, pcs.; $(\beta_{bas}^{\Pr St})_n, (\beta_{aux}^{\Pr St})_n$ — the share of time for execution of the sets of basic and auxiliary actions within the n-th processing stage in the total labor intensity of the corresponding sets of actions within the technological process; $(\alpha_{ct}^{\Pr St})_n, (\alpha_{w}^{\Pr St})_n, (\alpha_{qwq}^{\Pr St})_n$, $(\alpha_{am}^{\Pr St})_n, (\alpha_{rep}^{\Pr St})_n, (\alpha_{el.en.}^{\Pr St})_n, (\alpha_{dif.}^{\Pr St})_n$ — the share of costs intended for the purchase of cutting tools and quick-wear equipment, payment of wages to production workers, amortization, maintenance and repair of technological equipment, payment of electricity and other costs, respectively, in the total cost of implementing the of the n-th processing stage in the total amount of costs for the corresponding calculation items spent on the implementation of the technological process.

At the second control level, three groups of the targets are defined:

The first group of target indicators characterizing the accuracy of the geometric parameters of individual elements of the detail within the processing stage — Tr_{11}^{TechPr}.

The second group of target indicators characterizing the value of capital investments and operating costs for the implementation of individual processing stages — Tr_{12}^{TechPr}.

The third group of targets, which characterizes the sets of basic and auxiliary actions within the processing stages — Tr_{13}^{TechPr}.

The groups of the target indicators Tr_{11}^{TechPr}, Tr_{12}^{TechPr}, Tr_{13}^{TechPr} have the following structure (10)-(13):

$$Tr_{11}^{\Pr St} = \{AcIn_1^{TeachOp}, \ldots AcIn_k^{TeachOp}\}, \tag{10}$$

$$\begin{gathered} Tr_{12}^{\Pr St} = \{(CAPEX^{\Pr St})_1, \ldots, (CAPEX^{\Pr St})_n \\ (OPEX^{\Pr St})_1, \ldots, (OPEX^{\Pr St})_n\}, \end{gathered} \tag{11}$$

$$\begin{gathered} Tr_{13}^{\Pr St} = \{(T_{bas}^{\Pr St})_1, \ldots (T_{bas}^{\Pr St})_n, (T_{aux}^{\Pr St})_1, \\ \ldots, (T_{aux}^{\Pr St})_n\}, \end{gathered} \tag{12}$$

$$\begin{gathered} Tr_{11}^{\Pr St} \subset Tr^{\Pr St},\ Tr_{12}^{\Pr St} \subset Tr^{\Pr St}, \\ Tr_{13}^{\Pr St} \subset Tr^{\Pr St}, \end{gathered} \tag{13}$$

where $Tr^{\Pr St}$ — the multiple individual optimization criteria within the second control level; $AcIn_k^{TeachOp}$ – the index of accuracy of geometric parameters within the k-th technological operation; $(CAPEX^{\Pr St})_n$ – the amount of capital investments for the implementation of the n-th processing stage, rubles; $(OPEX^{\Pr St})_n$ — the amount of operating costs for the implementation of the n-th processing stage, rubles; $(T_{bas}^{\Pr St})_n$ – the labor intensity of performing a set of basic actions within the n-th processing stage, min; $(T_{aux}^{\Pr St})_n$ – the labor intensity of the set of auxiliary actions within the nth treatment stage, min.

The vector optimization criterion for the sec-ond control level has the following structure (14):

$$\begin{aligned} F^{\Pr St}(U_2) = (&AcIn_k^{TechOp}(U_2), \\ &(CAPEX^{\Pr St})_n(U_2), \\ &(OPEX^{\Pr St})_n(U_2), \\ &(T_{bas}^{\Pr St})_n(U_2)), \end{aligned} \tag{14}$$

The third control level describes the state of the object within the processing stage (Figure 5). The object can

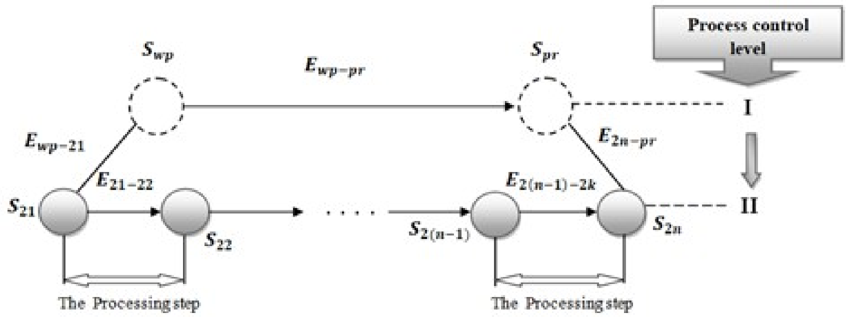

Figure 4. The graph of the second control level

be described by the following sequence of intermediate states (15):

$$S_{2(k-1)} \to S_{31}^{2(n-1)-2n} \to \ldots \to S_{3}^{2(n-1)-2n} \to S_{3k}^{2(n-1)-2n} \to S_{2n}, \quad (15)$$

where $S_{3k}^{2(n-1)-2n}$ — the k-th intermediate state of the object at the third control level; k — the number of intermediate object states in the third control level.

The condition for the transition of the control object from the state $S_{3(k-1)}^{2(n-1)-2n}$ to the state $S_{3k}^{2(n-1)-2n}$ can be described by the following expression (16)–(17):

$$S_{3k}^{2(n-1)-2n} = f(S_{3(k-1)}^{2(n-1)-2n}, U_3), \quad (16)$$

$$U_3 = \{(\beta_{bas}^{TechOp})_k, (\beta_{aux}^{TechOp})_k, (\alpha_{ct}^{TechOp})_k, (\alpha_{w}^{TechOp})_k, (\alpha_{qwq}^{TechOp})_k, (\alpha_{ct}^{TechOp})_k, (\alpha_{rep}^{TechOp})_k, (\alpha_{el.en.}^{TechOp})_k, (\alpha_{dif}^{TechOp})_k, (\gamma_i^{EmWp})_k, (\gamma_i^{In\,\mathrm{Pr}\,Sys})_k\} \quad (17)$$

where U_3 — the vector of the control parameters within the third control level; $(\beta_{bas}^{TechOp})_k, (\beta_{aux}^{TechOp})_k$ — the share of time to perform the sets of basic and auxiliary actions within the of the k-th technological operation in the total labor intensity of the corresponding sets of actions within the n-th processing stage; $(\alpha_{ct}^{TechOp})_k$, $(\alpha_{w}^{TechOp})_k, (\alpha_{qwq}^{TechOp})_k, (\alpha_{ct}^{TechOp})_k$, $(\alpha_{rep}^{TechOp})_k, (\alpha_{el.en.}^{TechOp})_k$, $(\alpha_{dif}^{TechOp})_k$ — the share of costs intended for the purchase of cutting tools and quick-wear equipment, payment of wages to production workers, amortization, maintenance and repair of technological equipment, payment of electricity and other costs, respectively, in the total cost of implementing of the k-th technological operation in the total cost of the corresponding calculation items for the implementation of the n-th processing stage; $(\gamma_i^{EmWp})_k$ — the error value for the i-th geometric parameter caused by the inaccuracy of the workpiece emplacement, formed at the k-th technological operation within the general tolerance field for the corresponding parameter; $(\gamma_i^{In\,\mathrm{Pr}\,Sys})_k$ — the error value for the i-th geometric parameter caused by inaccuracy of adjustment of the technological system to the size formed at the k-th technological operation within the general tolerance field for the corresponding parameter.

At the third control level, three groups of targets are defined:The first group of target indicators that characterizes the accuracy of the geometric paparameters of individual detail elements within the technological operation — Tr_{11}^{TrchOp}.
The second group of target indicators characterizing the values of operating costs for the implementation of individual technological operations — Tr_{12}^{TrchOp}.
The third group of target indicators, which characterizes the sets of basic and auxiliary actions within the technological operations - Tr_{13}^{TrchOp}.

The groups of the target indicators Tr_{11}^{TrchOp}, Tr_{12}^{TrchOp}, Tr_{13}^{TrchOp} have the following structure (18)-(21):

$$Tr_{11}^{TrchOp} = \{AcIn_1^{TechTr}, \ldots, AcIn_m^{TechTr}, (Err)_1^{EmWp}, \ldots, (Err)_k^{EmWp}, (Err)_1^{In\,\mathrm{Pr}\,Sys}, \ldots, (Err)_k^{In\,\mathrm{Pr}\,Sys}. \quad (18)$$

$$Tr_{12}^{TrchOp} = \{OPEX_1^{TechOp}, \ldots OPEX_k^{TechOp}\}. \quad (19)$$

$$Tr_{13}^{TrchOp} = \{(T_{bas}^{TechOp})_1, \ldots, (T_{bas}^{TexhOp})_k, (T_{aux}^{TechOp})_1, \ldots (T_{aux}^{TechOp})_k\}. \quad (20)$$

$$Tr_{11}^{TrchOp} \subset Tr^{TrchOp},\ Tr_{12}^{TrchOp} \subset Tr^{TrchOp},\ Tr_{13}^{TrchOp} \subset Tr^{TrchOp}, \quad (21)$$

where Tr^{TrchOp} — the multiple individual optimization criteria at the third control level; $AcIn_m^{TechTr}$ — the index of accuracy of geometric parameters within the m-th technological transition; $(Err)_k^{EmWp}$ — the error value caused by inaccuracy of the workpiece emplacement within the k-th technological operation, μm; $(Err)_k^{In\,\mathrm{Pr}\,Sys}$ — the error value caused by inaccuracy of adjustment of the process system to the size within the

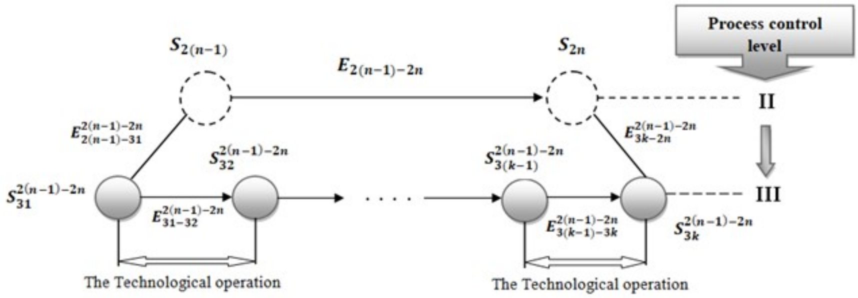

Figure 5. The graph of the third control level

k-th technological operation, μm; $OPEX_k^{TechOp}$ – the amount of operating costs for the implementation of the k-th technological operation, rubles; $(T_{bas}^{TexhOp})_k$ – the labor intensity of performing a set of basic actions within the k-th technological operation, min; $(T_{aux}^{TechOp})_k$ – the labor intensity of the set of auxiliary actions within the k-th technological operation, min.

Thus, the vector optimization criterion for the third control level is (22):

$$F^{TechOP}(U_3) = (AcIn_m^{TechTr}(U_3), (Err)_k^{EmWp}(U_3),$$

$$(Err)_m^{In\,\Pr Sys}(U_3), OPEX_k^{TechOp}(U_3),$$

$$(T_{bas}^{TechOp})_k(U_3), (T_{aux}^{TechOp})_k(U_3)) \qquad (22)$$

The fourth control level describes the state of the object within technological transition. In this case, the change in the state of the control object is described by the following sequence of intermediate states (Figure 6) (23):

$$S_{41}^{3(k-1)-3k} \to \ldots \to S_{4(m-1)}^{3(k-1)-3k} \to S_{4m}^{3(k-1)-3k}, \qquad (23)$$

where m -the number of states of the control object within the process operation (the number of process transitions in the process operation structure), pcs.

The condition for the transition of the control object from the state $S_{4(m-1)}^{3(k-1)-3k}$ to the state $S_{4m}^{3(k-1)-3k}$ can be described by the following expression (24)-(25):

$$S_{4m}^{3(k-1)-3k} = f(S_{4(m-1)}^{3(k-1)-3k}, U_4). \qquad (24)$$

$$\begin{aligned} U_4 = (&(\beta_{bas}^{TechTr})_m, (\beta_{aux}^{TechTr})_m, (\alpha_{ct}^{TechTr})_m, \\ &(\alpha_w^{TechTr})_m, (\alpha_{qwq}^{TechTr})_m, (\alpha_{am}^{TechTr})_m, \\ &(\alpha_{rep}^{TechTr})_m, (\alpha_{el.en.}^{TechTr})_m, (\alpha_{dif}^{TechTr})_m), \end{aligned} \qquad (25)$$

where U_4 — the vector of control parameters at the fourth control level; $(\beta_{bas}^{TechTr})_m$, $(\beta_{aux}^{TechTr})_m$ — the share of time to perform the sets of basic and auxiliary actions within the m-th technological transition, respectively, in the total labor intensity of the corresponding complexes of actions of the k-th technological operation; $(\alpha_{ct}^{TechTr})_m$, $(\alpha_w^{TechTr})_m$, $(\alpha_{qwq}^{TechTr})_m$, $(\alpha_{qwq}^{TechTr})_m$, $(\alpha_{am}^{TechTr})_m$, $(\alpha_{rep}^{TechTr})_m$, $(\alpha_{rep}^{TechTr})_m$, $(\alpha_{dif}^{TechTr})_m$ — the share of costs intended for the purchase of cutting tools and quick-wear equipment, payment of wages to production workers, amortization, maintenance and repair of technological equipment, payment of electricity and other costs, respectively in the total cost for the m-th technological transition in the total cost of the corresponding calculation items for the implementation of the k-th technological operation.

At the fourth control level, three groups of targets are defined:

> The first group of target indicators that characterizes the accuracy of the geometric parameters of individual detail elements within the technological transition — Tr_{11}^{TrchTr},
> The second group of target indicators characterizing the values of operating costs for the relevant calculation items for the implementation of individual technological transitions — Tr_{12}^{TrchTr},
> The third group of target indicators, which characterizes the sets of basic and auxiliary actions within the technological transitions - Tr_{13}^{TrchTr}.

The groups of the target indicators Tr_{11}^{TrchTr}, Tr_{12}^{TrchTr}, Tr_{13}^{TrchTr} have the following structure (26)-(29):

$$Tr_{11}^{TrchTr} = \{AcIn_1^{TechTr}, \ldots, AcIn_m^{TechTr}\}, \qquad (26)$$

$$Tr_{12}^{TrchTr} = \{OPEX_1^{TechOp}, \ldots, OPEX_k^{TechOp}\}, \qquad (27)$$

$$\begin{aligned} Tr_{13}^{TrchTr} = \{&(T_{bas}^{TechOp})_1, \ldots, (T_{bas}^{TechOp})_k, \\ &(T_{aux}^{TechOp})_1, \ldots, (T_{aux}^{TechOp})_k\}, \end{aligned} \qquad (28)$$

$$Tr_{11}^{TrchTr} \subset Tr^{TrchTr},\ Tr_{12}^{TrchTr} \subset Tr^{TrchTr} \qquad (29)$$
$$Tr_{13}^{TrchTr} \subset Tr^{TrchTr},$$

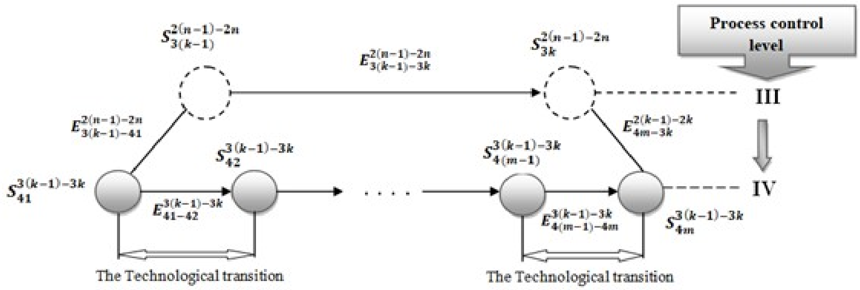

Figure 6. The graph of the third control level

where Tr^{TrchTr} — the multiple individual optimization criteria at the fourth control level; $AcIn_m^{TechTr}$ — index of accuracy of geometric parameters within the m-th technological transition; $OPEX_k^{TechOp}$ - the amount of operating costs for the implementation of the m-th technological transition, rubles.; $(T_{bas}^{TechOp})_k$ — the labor intensity of performing a set of basic actions within the m-th technological transition, min; $(T_{aux}^{TechOp})_k$ — the labor intensity of the set of auxiliary actions within the m-th technological transition, min.

Thus, the vector optimization criterion for the fourth control level is (30):

$$F^{TechTr}(U_4) = (AcIn_m^{TechTr}(U_4), OPEX_k^{TechOp}(U_4), (T_{bas}^{TechOp})_k, (U_4), (T_{aux}^{TechOp})_k). \quad (30)$$

The fifth control level describes the state of the object within working stroke and auxiliary transi-tions. In this case, the change in the state of the con-trol object is described by the following sequence of intermediate states (Figure 7) (31):

$$S_{51}^{4(m-1)-4m} \to \ldots \to S_{5(p-1)}^{4(m-1)-4m} \to \to S_{5p}^{4(m-1)-4m}, \quad (31)$$

where p — the number of states of the control object within the working stroke, pcs.

The condition of transition of the control object from the state $S_{5(p-1)}^{4(m-1)-4m}$ to the state $S_{5p}^{4(m-1)-4m}$ can be described by the following expression (32)- (33):

$$S_{5p}^{5(m-1)-4m} = f(S_{5(p-1)}^{4(m-1)-4m}, U_5), \quad (32)$$

$$U_5 = \{\beta_p^{WSt}, (\alpha_{ct}^{WSt})_p, (\alpha_w^{WSt})_p, (\alpha_{qwq}^{WSt})_p, (\alpha_{am}^{WSt})_p, (\alpha_{rep}^{WSt})_p, (\alpha_{el.en.}^{WSt})_p, (\alpha_{dif/}^{WSt})_p, (\gamma_i^{ElDif.})_{pm}^{WSt}, (\gamma_i^{Dim.W})_{pm}^{WSt}, (\gamma_i^{ThSt.})_{pm}^{WSt}, s_p, V_p, t_p\}, \quad (33)$$

where U_5 – vector of control parameters at the fifth control level; β_p^{WSt} — share of time aimed at performing the p-th working stroke in the total labor intensity of the complex of main actions of the m-th technological transition; $(\alpha_{ct}^{WSt})_p, (\alpha_w^{WSt})_p, (\alpha_{qwq}^{WSt})_p, (\alpha_{am}^{WSt})_p, (\alpha_{rep}^{WSt})_p, (\alpha_{el.en.}^{WSt})_p, (\alpha_{dif/}^{WSt})_p$ — the share of costs intended for the purchase of cutting tools and wear tools, payment of wages to production workers, depreciation, maintenance and repair of technological equipment, payment of electricity and other costs for the implementation of the p-th working stroke in the total cost of the corresponding calculation items for the implementation of the m-th technological transition; ; $(\gamma_i^{ElDif.})_{pm}^{WSt}$ — share of error caused by elastic deformations of the process system in the total processing error of the i-th geometric parameter within the implementation of the p-th working stroke; $(\gamma_i^{Dim.W})_{pm}^{WSt}$ — share of the error caused by dimensional wear of the cutting tool in the total error of processing the i-th geometric parameter within the implementation of the p-th working stroke; $(\gamma_i^{ThSt.})_{pm}^{WSt}$ — share of the error caused by thermal deformations of the process systems in the total processing error of the i-th geometric parameter within the implementation of the working stroke; s_p — feed value for p-th working stroke, mm/vol; V_p — cutting speed for p-th working stroke, m/min; t_p – cutting depth for p-th working stroke, mm.

At the fifth control level, three groups of targets are defined:

The first group of target indicators that characterizes the accuracy of the geometric parameters of individual detail elements within the working stroke - Tr_{11}^{WSt}.
The second group of target indicators characterizing the values of operating costs for the implementation of individual working stroke - Tr_{12}^{WSt}.
The third group of targets, which characterizes the labor intensity of individual work stroke - Tr_{13}^{WSt}.

Sets of particular optimization criteria within the fifth level of control Tr_{11}^{WSt}, Tr_{12}^{WSt}, Tr_{13}^{WSt} have the following structure (35)-(37):

$$Tr_{11}^{WSt} = \{\left(Err_i^{Dim.W}\right)_p^{WSt}, (Err_i^{lDif})_p^{WSt}, \left(Err_i^{ThSt.}\right)_p^{WSt}\} \quad (34)$$

$$Tr_{12}^{WSt} = \left\{OPEX_1^{WSt}, \ldots, OPEX_p^{WSt}\right\}, \quad (35)$$

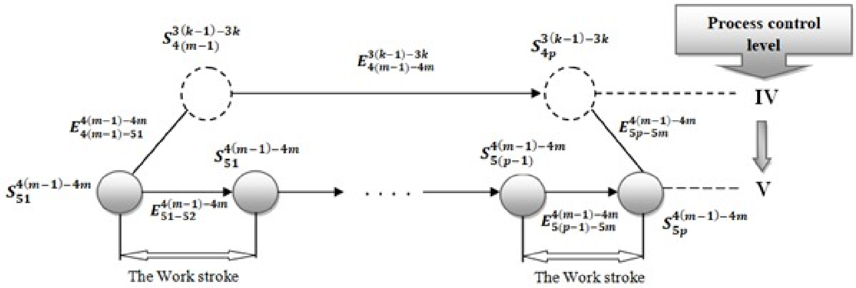

Figure 7. Graph of the fifth management level

$$Tr_{13}^{WSt} = \left\{ (T_{bas}^{WSt})_1, \ldots, (T_{bas}^{WSt})_p \right\}, \tag{36}$$

$$Tr_{11}^{WSt} \subset Tr^{WSt},\ Tr_{12}^{WSt} \subset Tr^{WSt},\ Tr_{13}^{WSt} \subset Tr^{WSt} \tag{37}$$

where Tr^{WSt} — the multiple individual optimization criteria at the fifth management level; $\left(Err_i^{Dim.W}\right)_p^{WSt}$ — the error value of the i-th parameter caused by dimensional wear of the cutting tool within the p-th working stroke, μm; $\left(Err_i^{ThSt.}\right)_p^{WSt}$ — the value of the error of the i-th parameter caused by thermal deformations of the technological system, within the framework of the p-th working stroke, μm; $(Err_i^{lDif})_p^{WSt}$ — the error value of the i-th parameter caused by elastic deformations of the process system within the p-th working stroke, μm; $(T_{bas}^{WSt})_p$ – the labour intensity of working stroke, min.; $OPEX_p^{WSt}$ - operating costs for working stroke.

The vector optimization criterion for the fifth control level is (38):

$$\begin{aligned} &F^{WSt}(U_5) = \\ &= ((Err_i^{Dim.W})_p^{WSt}(U_5), (Err_i^{ElDif})_p^{WSt}(U_5), \\ &(Err_i^{ThSt.})_p^{WSt}(U_5), OPEX_p^{WSt}(U_5), \\ &(T_{bas}^{WSt})_p(U_5). \end{aligned} \tag{38}$$

2 Optimization of processing parameters.

Setting the problem: optimizing the parameters of the technological process of manufacturing the detail "Roller". Research object: technological process of the detail "Roller" (Figure 8). The detail made of dispersed-hardened composite alloy SAS-50.

As a result of optimization carried out at 1-4 control levels, the technological process structure was determined (Figure 9).

The structure of the technological process for the detail "Roller" was determined, which consists of two processing stages, 4 technological operations, 8 technological transitions and 16 working stroke. The processing method is turning.

Within the fifth control level the parameters for working stroke are optimized. The following intervals and steps of variation of cutting parameters for machining of external cylindrical surfaces are defined:

The first processing stage:

$$V \in [250; 360],\ \Delta_v = 5,\ s \in [0,2; 1.5],\ \Delta_s = 0.1,$$

$$t \in [0,5; 2],\ \Delta_t = 0.1.$$

The second processing stage

$$V \in [80; 190],\ \Delta_v = 5,\ s \in [0,05; 0,2],\ \Delta_s = 0,01,$$

$$t \in [0,05; 0,4],\ \Delta_s = 0,01.$$

The following optimization criteria are defined for the working strokes:

The first technological operation (39):

$$(T_{bas}^{WSt})_{1\ldots7} \to \min. \tag{39}$$

The second technological operation (40):

$$(T_{bas}^{WSt})_{1\ldots2} \to \min. \tag{40}$$

The third technological operation (41):

$$(Err_i^{Dim.W})_{1,2,4}^{WSt} \to \min,\ (Err_i^{ElDif})_{1,2,4}^{WSt} \to \min;$$

$$(Err_i^{ThSt})_{1,2,4}^{WSt} \to \min;\ (T_{bas}^{WSt})_3 \to \min. \tag{41}$$

The fourth technological operation (42):

$$(Err_i^{Dim.W})_{5,7}^{WSt} \to \min,\ (Err_i^{ElDif})_{5,7}^{WSt} \to \min;$$

$$(Err_i^{ThSt})_{5,7}^{WSt} \to \min,\ (T_{bas}^{WSt})_6 \to \min. \tag{42}$$

Figure 10 shows the plots of the dependence of targets on cutting parameters for finishing processing of the external cylindrical surface $\phi 20h6$.

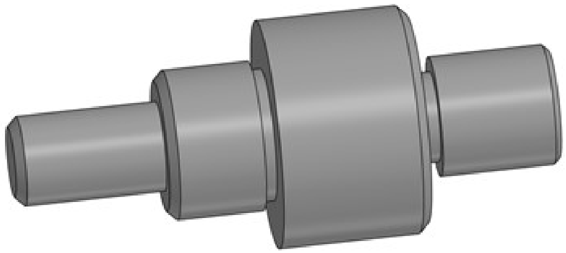

Figure 8. Solid Model of detail "Roller"

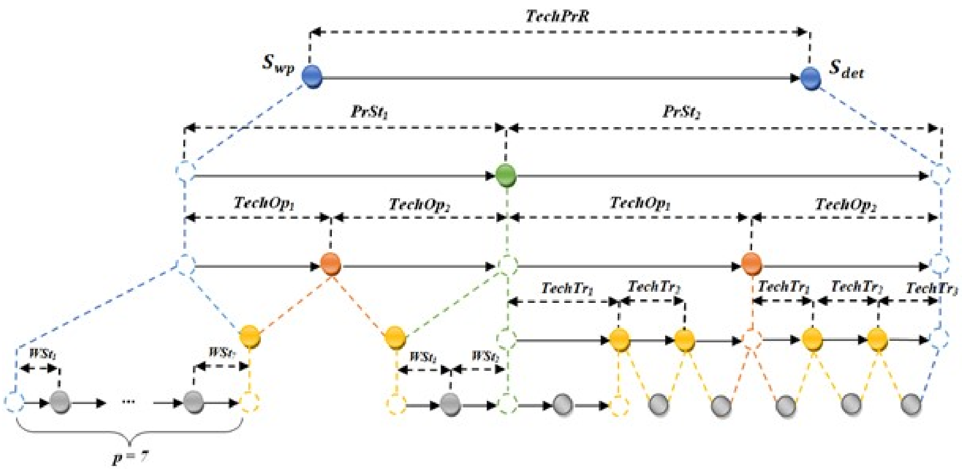

Figure 9. The structural model of the technological process of the detail "Roller"

3 Conclusions.

Taking into account the condition (42), the following optimal values of processing parameters for working strokes were established:

1. The first technological operation: $V_{1..7} = 340m/min$; $s_{1..7} = 1,3mm/vol$; $t_{1..7} = 2mm$.
2. The second technological operation: $V_{1..2} = 340m/min$; $s_{1..2} = 1,3mm/vol$; $t_{1..2} = 2mm$.
3. The third technological operation: $V_{1..2} = 125m/min$; $s_{1..2} = 0,1mm/vol$; $t_{1..2} = 0,3mm$; $V_3 = 345; m/min$; $s_3 = 0,4mm/vol$; $V_4 = 80m/min$; $s_4 = 0,05mm/vol$; $t_4 = 0,15mm$.
4. The fourth technological operation: $V_1 = 165m/min$; $s_1 = 0,08mm/vol$; $t_1 = 0,35mm$; $V_2 = 345; m/min$; $s_2 = 0,4mm/vol$; $V_3 = 80m/min$; $s_3 = 0,05mm/vol$; $t_3 = 0,15mm$.

As a result of multi-criteria optimization, the following target values were determined:

1. The first technological operation: $(Err_i^{Dim.W})_{1..7}^{WSt} = 5,01\ \mu m$; $(Err_i^{ElDif})_{1..7}^{WSt} = 35,1\ \mu m$; $(Err_i^{ThSt})_{1..7}^{WSt} = 29,2\ \mu m$; $OPEX_{1..7}^{WSt} = 9,25rub$; $(T_{bas}^{WSt})_{1..7} = 1,23$ min .
2. The second technological operation: $(Err_i^{Dim.W})_{1..2}^{WSt} = 5,01\ \mu m$; $(Err_i^{ElDif})_{1..2}^{WSt} = 35,1\ \mu m$; $(Err_i^{ThSt})_{1..2}^{WSt} = 29,2\ \mu m$; $OPEX_{1..2}^{WSt} = 5,1rub$; $(T_{bas}^{WSt})_{1..2} = 0,68$ min .
3. The third technological operation: $(Err_i^{Dim.W})_{1..2}^{WSt} = 2,1\ \mu m$; $(Err_i^{ElDif})_{1..2}^{WSt} = 8,1\ \mu m$; $(Err_i^{ThSt})_{1..7}^{WSt} = 10,3\ \mu m$; $OPEX_{1..2}^{WSt} = 1,65rub$; $(T_{bas}^{WSt})_{1..2} = 0,22$ min, $(Err_i^{Dim.W})_3^{WSt} = 4,5\ \mu m$; $(Err_i^{ElDif})_3^{WSt} = 16,3\ \mu m$; $(Err_i^{ThSt})_3^{WSt} = 11,2\ \mu m$; $OPEX_3^{WSt} = 0,9rub$; $(T_{bas}^{WSt})_3 = 0,12$ min, $(Err_i^{Dim.W})_4^{WSt} = 1,1\ \mu m$; $(Err_i^{ElDif})_4^{WSt} = 1,8\ \mu m$; $(Err_i^{ThSt})_4^{WSt} = 2,91\ \mu m$; $OPEX_4^{WSt} = 1,73rub$; $(T_{bas}^{WSt})_4 = 0,23$ min .
4. The fourth technological operation: $(Err_i^{Dim.W})_1^{WSt} = 2,2\ \mu m$; $(Err_i^{ElDif})_1^{WSt} = 10,4\ \mu m$; $(Err_i^{ThSt})_1^{WSt} = 11,2\ \mu m$; $OPEX_1^{WSt} = 1,5rub$; $(T_{bas}^{WSt})_1 = 0,24$ min; $(Err_i^{Dim.W})_2^{WSt} = 2,3\ \mu m$; $(Err_i^{ElDif})_2^{WSt} = 9,4\ \mu m$; $(Err_i^{ThSt})_2^{WSt} = 10,52\ \mu m$; $OPEX_2^{WSt} = 0,98rub$; $(T_{bas}^{WSt})_2 = 0,98$ min; $(Err_i^{Dim.W})_3^{WSt} = 2,1\ \mu m$; $(Err_i^{ElDif})_3^{WSt} = 2,3\ \mu m$; $(Err_i^{ThSt})_3^{WSt} = 2,9\ \mu m$; $OPEX_3^{WSt} = 0,11, rub$; $(T_{bas}^{WSt})_3 = 0,82$ min.

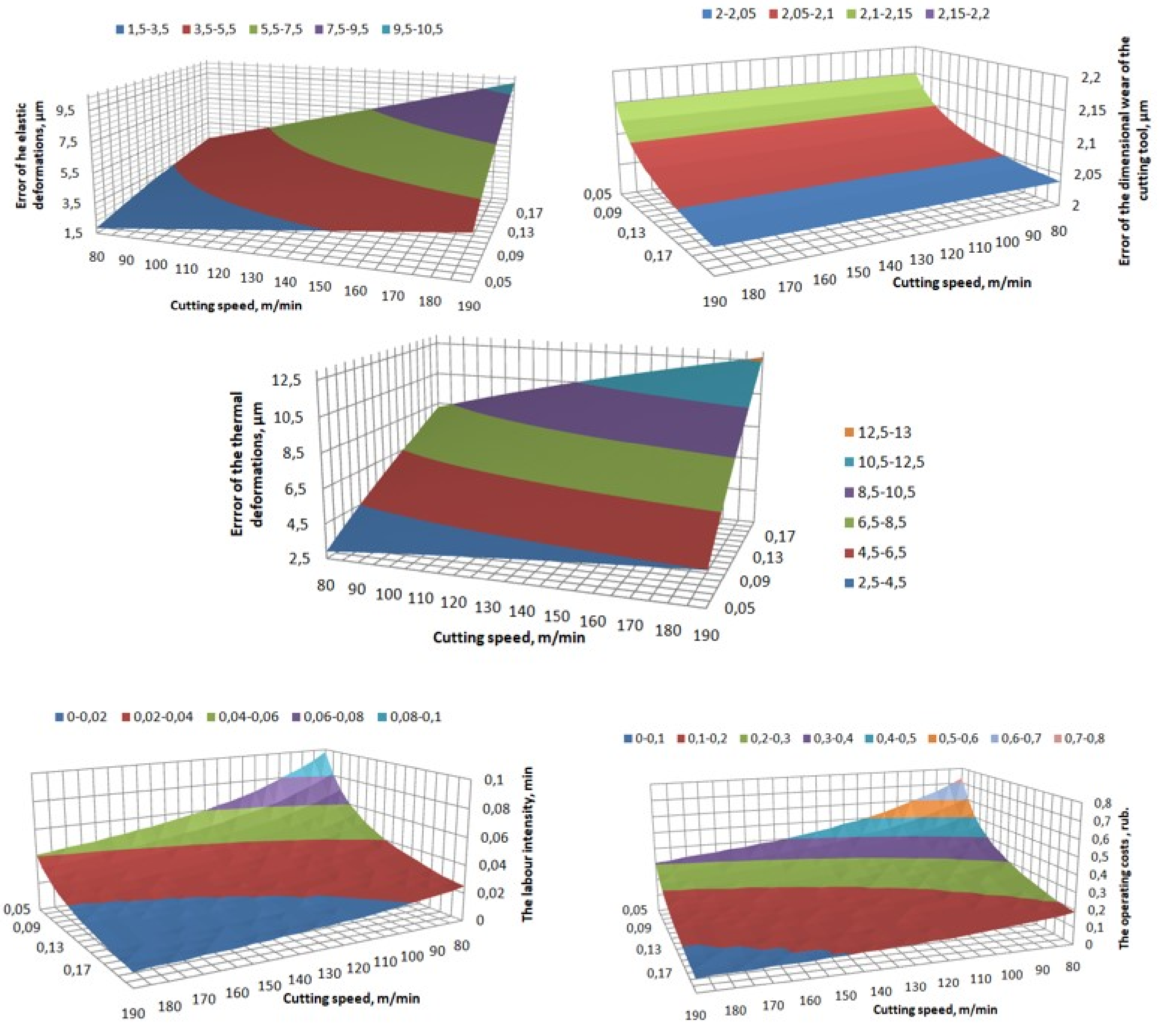

Figure 10. Plots of targets versus cutting parameters

According to the conditions (38,39,40,41), as a result of optimizing the cutting parameters, a reduc-tion in the processing error for the most accurate sur-faces in the range of 11.2-12.6% was achieved. For geometric elements with low manufacturing accuracy, the processing time was optimized according to the conditions (40,41). As a result of optimization, a re-duction in the complexity of manufacturing these el-ements in the range of 13.1-15.1% was achieved.

Optimizing process objectives is key to im-proving the efficiency of the product technological process. The hierarchy of goals presented in the struc-tural model allows to increase the efficiency of the technological process by detailed analysis and optimi-zation of the target indicators of individual structural elements of the model.

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