New methods and equipment for the machining of cross-axes parts- Case study

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Abstract: The processes and equipment for manufacturing, assembly, and control operations, adapted to the needs of modern industry, shall be determined according to the volume of production and the technical conditions imposed, at a level which ensures economic effects on the recovery of costs for their design and execution. The design-optimization algorithm, with the four working steps, applied on the case study presented, allows the determination of the optimal number and succession of technological processes, but also of new processing methods, based on a technological graph and optimization criteria. In the second step, determine for each technological operation the optimal orientation and fixation scheme of the analyzed part, combining elements of the set theory and the global utility method, with a method of simultaneous optimization of the orientation and fixation fundamentals for two different transformation areas with distinct quotas and conditions that need to be achieved. In the third step, is identified and analyzed several construction variants of structures for the equipment. By formulating a technologically adapted graph to describe structures of orientations, but also other structures, is obtained an associated mathematical model and optimization criteria for the optimum design variant of the orientation and fixation at the analyzed operation. When is desired a complete appreciation of all the technological operations, the fourth step of system optimization is proposed, which is also based on a technology graph and an associated mathematical model adapted to the evaluation of the analyzed types of equipment.

1. Introduction
The modernization of manufacturing processes obviously requires the development and evolution of technological equipment for work and control by making new solutions in the field of semi-finished devices for orientation and fixing, driving and support tools, upgrading of machine tools, allowing the use of new processing methods.

Current research [1-8] promotes a new concept, related to the complex optimization of manufacturing processes and equipment, for machine building technologies, on the basis of criteria of related importance, which have a different weighting depending on the objectives pursued.

The evolution of technological processes is necessarily linked to the increase in the performance of technological equipment for processing, assembly and control, thanks to the development of new special or modular structures, components and systems for guiding, fixing and multifunctional driving for the construction of tools, devices and machine tools.

In this document, after analysis of the technical documentation and working conditions, a new processing technology for the Tie Rod Body is proposed, outlining the type and sequence of technological operations suitable for machine tools in the equipment, optimal diagrams for the
orientation and fixing of semi-finished products, optimal variants of construction and operation of structures in the composition of work or control devices and equipment.

2. Successive-simultaneous method of optimizing technological processes and equipment

At the stage of the technological process, the characteristics and performance of the technological equipment that can ensure with certainty the accuracy, productivity and flexibility of processing, assembly or control of semi-finished products.

2.1. Method for designing and optimizing technological processes and equipment

The system-wide analysis of problems in the optimization of technological processes and equipment is determined by the need to highlight the multitude of factors that make it conditional, with a view to establishing rational solutions for the field of manufacturing engineering [1, 2, 5].

For these reasons, a combined design-optimization method (process and technological equipment) is proposed with three mandatory steps and one additional step, shown in figure 1.

![Figure 1. Method for optimizing combined processes and technological equipment.](image)

- **E01** - Determining the optimal number and sequence of technological operations;
- **E02** - Determination of the optimal orientation and fixing scheme for the semi-finished product;
- **E03** - Determining the optimal design variant of the device;
- **E04** - Establishing the optimum design variant of the process equipment in terms of technological processes.

3. Determining the optimal number and sequence of technological operations

For this purpose, the processing technology is presented on a case study, for the **Tie Rod Body**, which is a safety element in the **Steering System**, with the role of transmitting the movement from the steering box to the front wheels of the vehicle.

After the constructive-functional analysis of the drawing and of the overall drawing to which it belongs, the **Tie Rod Body** is in the class of parts with complex profile, with bidirectional crossed axes, implying some difficulty in carrying out the implementation of the technical conditions.

Compared to the existing technological process with a certain level of precision and productivity for a relatively simpler part, in the technology proposed for this more demanding part, is intended to emphasis the orientation and fixing phases of the semi-finished products, the constructive-functional optimization and configuration of devices with several work stations in certain operations and the construction of combined tools for simultaneous processing.

3.1. The mathematical model associated with the problem

It is considered that each operation or processing phase can be carried out by one or more processing processes, known or new ones that can be developed at that time.

Establishing optimal processing procedures requires the initial selection of those who best fit certain conditions that are imposed.

For the technology process under analysis, the set of processing variants coded in column X matrix can be expressed by the technology graph in figure 2:

- **x1** - Drilling roughing \((\varnothing22.5^{+0.12})\);
- **x2** - Drilling \((\varnothing10.8^{+0.1})\), bladeing \((85^{+0.5})\), chamfering \((2\times45^\circ)\), threading \((M12\times1.25)\);
- **x3** - Internal turning and crimping profile \((\varnothing28.45^{+0.1}; \varnothing31.5^{+0.25}; \varnothing33.1; 20^\circ)\);
x₄ - Turning outer channel (Ø22.5±0.12);
x₅ - Thread control (M12x1.25);
x₆ - Boring drilling, boring milling, crimping profile milling, drilling, bladeing, chamfering, threading (Ø22.5±0.12; Ø28.8±0.12 and 10.4; Ø31.5±0.25; Ø33.1 and 2°; Ø10.8±0.1x49±0.3; 8°±0.5; 2x45°; M12x1.25).

The processing variant x₆ is the solution proposed for the modernization of the technology in which several operations and phases, for two different areas of the semi-finished product, will be executed in a single operation with a more efficient processing equipment.

Figure 2. Primary technological graph of the analyzed operation.

Figure 3. Secondary technological graph of the analyzed operation.

The points (nodes) of the graph represent the moments of transformation of the geometry of the piece, M={1, 2, 3, 4, 5}, in this case, and the procedures (operations) encoded by xᵢ are the graph arcs. The column vector of the encoded operations is:

$$X = [x₁, x₂, x₃, x₄, x₅]ᵀ$$

For a better highlighting of the technological variants, the secondary technology graph is rewritten, with shorter circuits, as in figure 3.

The coded processing procedures have the following significance: x₁ = x₁ + x₂, x₆ = x₆, x₃ = x₃, x₄ = x₄, x₅ = x₅.

The column vector of the procedures defined in the secondary graph is:

$$X' = [x'_₁, x'_₂, x'_₃, x'_₄, x'_₅]ᵀ$$

For the formulation of the mathematical model, the incidence matrix of the procedures used is introduced, but also the partial Tc, Rc matrices of the tolerances and roughnesses capable, the line matrices Tp, Rp of the tolerances and roughnesses prescribed [2], after which the system of inoculations is written and solved respecting the conditions ∑₁ = 1 and x₃ = v 0.

Write down the matrix related to the graph, noted with A, as you navigate the graph clockwise (3).

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 & -1 \\ -1 & -1 & 1 & 0 & 0 \\ 3 & 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix}$$ (3)
The positive side of the incidence matrix is identified \( (A^+) \), which takes into account, when completing the graph, only the positive elements (starting from the node), denoted by +1; the negative ones (-1) are 0:

\[
A^+ = \begin{pmatrix}
1 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1 \\
\end{pmatrix}
\] (4)

Square matrices \( T_c \) and \( R_c \) are:

\[
T_c = \begin{pmatrix}
0.12 & 0 & 0 & 0 & 0 \\
0 & 0.1 & 0 & 0 & 0 \\
0 & 0 & 0.12 & 0 & 0 \\
0 & 0 & 0 & 0.15 & 0 \\
0 & 0 & 0 & 0 & 0.05 \\
\end{pmatrix}, \quad R_c = \begin{pmatrix}
3.2 & 0 & 0 & 0 & 0 \\
0 & 3.2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.63 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 3.2 \\
\end{pmatrix}
\] (5)

Line matrices of prescribed tolerances and roughnesses \( T_p \) and \( R_p \) are:

\[
T_p = [0.24 \ 0.2 \ 0.25 \ 0.2 \ 0.1]^t, \quad R_p = [3.2 \ 3.2 \ 3.2 \ 6.3 \ 3.2]^t
\] (6)

\( U \) is the column matrix with \( n \) elements equal to 1, of the form:

\[
U = [1 \ 1 \ 1 \ 1 \ 1]^t
\] (7)

The mathematical model for nodes 1 and 2 is of the form:

\[
\begin{cases}
\min(C \cdot X) \\
A^+ \cdot X = U \\
A^+ \cdot (T_c \cdot X) \leq T_p \\
A^+ \cdot (R_c \cdot X) \leq R_p \\
x_j = 1 \ \forall \ 0
\end{cases}
\]

\[
\begin{cases}
\min(c_6 \cdot x_6 + c_1 \cdot x_1 + c_2 \cdot x_2) \\
x_6 + x_1 + x_2 = 1 \\
T_{c6} \cdot x_6 + T_{c1} \cdot x_1 + T_{c2} \cdot x_2 \leq T_p \\
R_{c6} \cdot x_6 + R_{c1} \cdot x_1 + R_{c2} \cdot x_2 \leq R_p \\
x_j = 1 \ \forall \ 0
\end{cases}
\] (8)

After replacing the values and solving the mathematical model, the optimal variant of the proposed technological process is of the form presented in the relation:

\[
\text{VO}_{\text{pt}} = [x_6 \ x_3 \ x_4 \ x_5]
\] (9)

4. Method for optimizing the orientation and fixing scheme of the semi-finished product

In the papers [1, 5, 9-11], several optimization methods are presented, from the simplified one to the more complex SEFA methodology, which establishes the optimal orientation and fixing scheme (O-OFS) of the semi-finished products based on the analysis of the stages, phases and significant activities of the existence of a product.
In all these cases the optimization method is applied separately, for each processing area, depending on the technical considerations and the type of operation.

The technological process $x_s$ of the optimal variant of the technological process requires the establishment of O-OFS simultaneously for two different areas of the semi-finished product, which will be processed in the same operation.

For these reasons, in the second stage of the design-optimization is proposed the method of simultaneous establishment of O-OFS for the semi-finished Tie Rod Body, combining elements of set theory and the global utility method with the methodology of optimization of the basis for targeting and fixing the semi-finished products, adapted to two different processing areas, which have specific quotas and conditions to achieve.

4.1. Development of possible technical orientation systems (PT-OS)

After a constructive-functional analysis of the Tie Rod Body as a working drawing and the assembly to which it belongs, the method of optimization of the orientation and fastening bases presented in the work with the following sequence must be followed:

**A01. Operation sketch**
- Joint head operation;
- Joint arm operation.

In the existing variant, these two processing areas are executed in two distinct operations.

In the sketch of the operation in figure 4 are presented the necessary elements for the analysis of the quotas and the technical conditions imposed that will generate the optimum variant of orientation and fixation of the semi-finished product.

![Figure 4. Operation sketch.](image-url)
A02. **Highlighting the technical conditions**

Table 1 specifies the quotas and the conditions imposed the processing areas and the quotation bases for the analyzed operation.

**Table 1. The quotas and conditions imposed, the processing areas and the quotation bases.**

| No. | cd. | Technical conditions imposed | Processing area | Dimension basis | Surfaces that determine them | Max. deviation | Deviations according |
|-----|-----|------------------------------|-----------------|----------------|-----------------------------|----------------|---------------------|
| C1  | Ø33.1 and 20° | Surface 19 | Surface axis 3 | Surface 3 | ±0.2 | SR EN 227668-1:1995 |
| C2  | 10.4 | Surface 1 | Surface axis 8 | Surface 8 | ±0.2 | SR EN 227668-1:1995 |
| C3  | 3.5° | Surface 1 | Surface 26 | Surface 26 | - | - |
| C4  | Ø28.8° | Surface 17 | Surface axis 3 | Surface 3 | - | - |
| C5  | 6.9 | Surface 18 | Surface axis 8 | Surface 8 | ±0.2 | SR EN 227668-1:1995 |
| C6  | 7.3 | Surface 6 | Surface axis 8 | Surface 8 | ±0.2 | SR EN 227668-1:1995 |
| C7  | 16.5 | Surface 18 | Surface 21 | Surface 21 | ±0.2 | SR EN 227668-1:1995 |
| C8  | 140° | Surface 20 | Surface 16 | Surface 16 | ±10° | SR EN 227668-1:1995 |
| C9  | S17, S19, S16 | Surface axis 3 | Surface axis 3 | Surface 3 | 0.3 | SR EN 227668-1:1995 |
| C10 | - | Surface 16 | Sv | Sv | ±0.4 | SR EN 227668-1:1995 |
| C11 | Axis S16, S17, S19, S20 | Surface axis 8 | Surface 8 | ±0.05 | - |
| C12 | Ø10.8 | Surface 22 | Surface axis 8 | Surface 8 | ±0.1 | SR EN 227668-1:1995 |
| C13 | 85.0° | Surface 24 | Surface axis 3 | Surface 3 | - | - |
| C14 | 49.0° | Surface 22 | Surface 24 | Surface 24 | - | - |
| C15 | - | Axis S22 | Surface axis 3 | Surface 3 | 0.5 | SR EN 227668-1:1995 |
| C16 | - | Surface 22 | Surface axis 8 | Surface 8 | 0.5 | SR EN 227668-1:1995 |
| C17 | 12 | Surface 24 | Surface 9 | Surface 9 | ±0.5 | SR EN 227668-1:1995 |
| C18 | - | Surface 24 | Surface axis 22 | Surface 22 | 0.1 | SR EN 227668-1:1995 |

Conditions C1, C2, ..., C11 are for head joints, and C12, C13, ..., C18 are for arm joints, the two better areas of the semi-finished product will be processed in the same operation.

For the analysis and the realization of the two groups of conditions in the same operation it is proposed to formulate additional conditions of connection between them, in this case it is C10, a new method of simultaneous-successive processing of the two zones and a rotary deposit with high precision and productivity.

A03. **Selection of technical conditions**

- Note with $M_1$ and formulate the set of technical conditions required for this operation, for head joint:
  \[
  M_1 = \{c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8, c_9, c_{10}, c_{11}\} \text{ or } M_1 = \{c_i | x \in \mathbb{I}^+, x \leq 11\} \tag{10}
  \]

- Note with $M_2$ and formulate the set of technical conditions required for this operation, for the joint arm:
  \[
  M_2 = \{c_{12}, c_{13}, c_{14}, c_{15}, c_{16}, c_{17}, c_{18}\} \text{ or } M_2 = \{c_i | x \in \mathbb{I}^+, 11 < x \leq 18\} \tag{11}
  \]

- In order to identify the surface of the part that ensures the best fit for the technological operation under analysis, it is necessary as a selection criterion, from the set of conditions highlighted, which of them are directly related to the orientation of the part on the supports of the device and ensures with higher precision.
Applying this condition is obtained:

\[ M_{1,0} = \{ c_2, c_5, c_6, c_9, c_{10} \} \]  \hspace{1cm} (12)

\[ M_{2,0} = \{ c_{13}, c_{15}, c_{16} \} \]  \hspace{1cm} (13)

The additional connection condition between the two processing areas is the condition C10. The meeting of the two sets \( M_{1,0} \) and \( M_{2,0} \) is a set consisting of all the elements of the two sets, which are related to the orientation of the blank in the device:

\[ M_{1,0} \cup M_{2,0} = \{ c_x \in M_{1,0} \text{ sau } c_x \in M_{2,0} \} \]  \hspace{1cm} (14)

\[ M_{1,0} \cup M_{2,0} = \{ c_2, c_5, c_6, c_9, c_{10}, c_{13}, c_{15}, c_{16} \} \]  \hspace{1cm} (15)

**A04. Geometrization of determining conditions**

Conditions C2, C5, ..., C16 are determining, important, necessary and obligatory conditions in the orientation of the semi-finished product, which expresses the connection between the geometrical elements of the surfaces to be processed and those of the dimension bases.

| Condition | Element 1 | Element 2 | Element 3 | Element 4 |
|-----------|-----------|-----------|-----------|-----------|
| C2        | S_1      | 10.4      | Dx_8-x_8  |           |
| C5        | S_{18}   | 6.9       | Dx_8-x_8  |           |
| C6        | S_{20}   | 7.3       | Dx_8-x_8  |           |
| C9        | S_{16}   |           | Dz_3-z_3  |           |
| C10       | S_{16}   |           |           | Sv        |
| C13       | S_{23}   | 85±0.5    | Dz_3-z_3  |           |
| C15       | Dx_{22}-x_{22} | ⊥ | Dz_3-z_3  |           |
| C16       | S_{22}   |           | D_{8}-x_8 |           |

**A05. Extreme conditions selection**

S_1, S_{18}, S_{26}, S_{16}, S_{24}, Dx_{22}-x_{22}, S_{22}, they are the *extreme directors*, they depend on the tool and they are reference elements. Dx_8-x_8, Dz_3-z_3, Sv, they are *extremely dependent*, because they depend on dimensions or conditions on the extreme ends and they ensure the orientation of the semi-finished product in the device.

**A06. Explanation of the dependent extremes**

The dependent ends will be expressed by real, tangible elements, which correspond on surfaces, straight lines or points of the workpiece.

| Condition | Element 1 | Element 2 | Element 3 | Element 4 |
|-----------|-----------|-----------|-----------|-----------|
| C2        | S_1      | 10.4      | Dx_8-x_8  |           |
| C5        | S_{18}   | 6.9       | Dx_8-x_8  |           |
| C6        | S_{20}   | 7.3       | Dx_8-x_8  |           |
| C9        | S_{16}   |           | Dz_3-z_3  |           |
| C10       | S_{16}   |           |           | Dx_8-x_8;Pk |
| C13       | S_{23}   | 85±0.5    | Dz_3-z_3  |           |
| C15       | Dx_{22}-x_{22} | ⊥ | Dz_3-z_3  |           |
| C16       | S_{22}   |           | D_{8}-x_8 |           |

**A07. Ordering the dependent extremes**

According to the criterion of frequency or degrees of freedom canceled the order is:

E_1 Dx_8-x_8; E_{II} Dz_3-z_3; E_{III} Pk
The ordered dependent ends are geometrical elements of the workpiece that have the function of dimensioning and orientation.

**A08. Symbolization of the materialization of the ordered dependent extremes**

The graphic signs from the information symbolization for each extreme are placed on the drawing in the operation sketch, thus:

\[ E_1 \quad D_{x_8-x_8} \quad (1) \quad (2) \quad (3) \quad (4) \quad (5) \quad (6) \quad (7) \quad (8) \quad (9) \quad (10) \]

\[ E_{II} \quad D_{z_3-z_3} \quad (5) \quad (6) \quad (7) \]

\[ E_{III} \quad Pk : \text{The supports (6), (7), after blocking, cancel Rx and become (6*), (7*), providing technical guidance schemes possible (PT-OS).} \]

**A09. Symbolization of auxiliary supports**

- It's not necessary.

**A10. Symbolization of the additional supports**

For the semi-finished product, the orientation elements (6) and (7) will be multifunctional orientation and stiffening supports with subsequent self-assembly and locking.

**A11. Establishing possible technical guidance schemes (PT-OS)**

In table 2, the ordered dependent extremes, with the symbolization of the information associated with the reactions, the conditions determined by their permissible errors must be completed, after which combinations of symbols are made for the three extremes defining the construction of a device, so that the maximum number of degrees of freedom cancelled does not exceed 6.

**Table 2. Centralization of PT-OS and TA-OS.**

| No. | PT-OS | E₁ Dₓ₈₋ₓ₈ | E₁ Dₓ₈₋ₓ₈ | E₃ Pk | C2 | C5 | C6 | C9 | C10 | C13 | C15 | C16 | TA-OS |
|-----|-------|------------|------------|-------|----|----|----|----|----|----|----|----|-------|
| 1   | X     | X          | X          | 0.867 | 0.867 | 0.867 | 0 | 0 | 0 | 0 | 0.867 |
| 2   | X     | X          | X          | 0.867 | 0.867 | 0.867 | 0 | 0 | 0 | 0 | 0.867 |
| 3   | X     | X          | X          | 0.842 | 0.842 | 0.842 | 0 | 0 | 0 | 0.842 | 0.842 |
| 4   | X     | X          | X          | 0.842 | 0.842 | 0.842 | 0 | 0 | 0 | 0.842 | 0.842 |
| 5   | X     | X          | X          | 0.16  | 0.16  | 0.16  | 0 | 0.75 | 0 | 0 | 0.75 |
| 6   | X     | X          | X          | 0.16  | 0.16  | 0.16  | 0 | 0.75 | 0 | 0 | 0.75 |
| 7   | X     | X          | X          | 0.16  | 0.16  | 0.16  | 0 | 0 | 0 | 0 | 0.16 | X |
| 8   | X     | X          | X          | 0.16  | 0.16  | 0.16  | 0 | 0 | 0 | 0 | 0.16 | X |
| 9   | X     | X          | X          | 0    | 0    | 0    | 0 | 0 | 0 | 0 | 0 | X |
| 10  | X     | X          | X          | 0    | 0    | 0    | 0 | 0 | 0 | 0 | 0 | X |

The symbols 6* and 7* are the same supports 6 and 7, which, after blocking, cancel a degree of freedom (Rx), for the extreme Pk.

**4.2. Technical selection of orientation schemes**

The allowable orientation errors are calculated ($\varepsilon_{oa}$) and go to the table. The equation is (16):
\[ \varepsilon_{oa} = \begin{pmatrix} 1 & 1 \\ 2 & 3 \end{pmatrix} \cdot T \]  

where: T- is the tolerance of the piece to the analyzed condition.

The actual orientation errors are calculated \( \varepsilon_{or} \), determined by clearances or non-compliance of the dimensioning bases (DB) with the guide bases (GB) and are placed in the table. The equations in the papers [11] are:

- for clearances:

\[ \varepsilon_{or} = \left( \frac{vL_{x}}{u_{1}} \right)^{2} \cdot j_{1}^{2} + \left( \frac{vL_{y}}{u_{2}} \right)^{2} \cdot j_{2}^{2} \]  

(17)

- for non-compliance of the dimensioning bases (DB) with the guide bases (GB):

\[ \varepsilon_{or} = \left( \frac{vL_{x}}{u_{1}} \right)^{2} \cdot T_{i}^{2} + \left( \frac{vL_{y}}{u_{2}} \right)^{2} \cdot T_{i}^{2} \]  

(18)

The actual orientation errors are compared with the admissible ones and the variants that fulfill the condition \( \varepsilon_{or} < \varepsilon_{oa} \) because all the errors analyzed, they become technical acceptable orientation schemes (TA-OS) that will ensure with certainty the accuracy of the processing of the device.

4.3. Economic selection of technically acceptable orientation schemes

The four technically acceptable orientation schemes (TA-OS), (variants 7, 8, 9 and 10) they are evaluated according to the global utility method, assigning values for the import coefficients according to how they respond favorably to the associated economic criteria, which are then given in the table 3.

After completion of the importance coefficients, symbol or combination of symbols that have the maximum value, is a local optimum for the extreme analyzed.

For the considered case, the optimal orientation scheme is:

\[
O-OS = \text{Optimum } E_{i} + \text{Optimum } E_{ii} + \text{Optimum } E_{iii}
\]

(19)

\[
O-OS = \left\{ \begin{array}{c}
(8) \\
(9) \\
(3) \\
(7)
\end{array} \right\}
\]

(20)

In a similar study, the optimal fixing scheme preceded by the symbol (11) is also established. Finally, the optimal orientation and fixation scheme (O-OFS), is:

\[
O-OFS = O-OS + O-FS = \left\{ \begin{array}{c}
(8) \\
(9) \\
(3) \\
(7) \\
(11)
\end{array} \right\}
\]

(21)
Table 3. Centralizing the criteria for economic optimization.

| No. TA-OS | Symbolization of information associated with dependent extremes | Criteria used (C-U) | Coefficients of importance (Ci) (Max.) | Decision |
|-----------|---------------------------------------------------------------|---------------------|----------------------------------------|----------|
|           |                                                               | CE1        CE2        CE3        CE4        CE5        CE6        Σ Ci |
| 1         |                                                               | 0.9  0.9  0.9  0.8  0.8  5.2 | Local optimum |
|           |                                                               | Optimum EI   |
| 2         |                                                               | 0.3  0.3  0.3  0.5  0.8  0.8  3 |             |
|           |                                                               |             |
| 3         |                                                               | 0.9  0.8  0.6  0.6  0.8  0.8  4.5 |             |
| 4         |                                                               | 0.9  0.9  0.6  0.8  0.8  0.8  4.8 | Optimum EII |
| 5         |                                                               | 0.9  0.8  0.6  0.6  0.8  0.8  4.5 |             |
| 6         |                                                               | 0.9  0.9  0.6  0.8  0.8  0.8  4.8 | Optimum EIII |

5. The design-optimization algorithm of the device construction

I. For this application the constructive variants of the orientation supports in O-OFS, are:

1. Short mobile prism:
   - x11: short mobile prism with guide directly into the body of the device;
   - x12: short mobile prism with guide in the wear bushing;
   - x13: short mobile prism with step guide on the body of the device;
   - x14: short mobile prism with guide, orientation and lock directly on the body of the device;

2. Extended flat base:
   - x21: support bolts;
   - x22: support plates;
   - x23: narrow support plate and oscillating support bolt;

3. Mobile centering bush:
   - x31: mobile ring with guide, orientation and lock on the body of the device;
   - x32: movable ring with guide in the wear ring;
   - x33: mobile case with step guide on the body of the device.

II. The construction variants of the supports are expressed by the graph in figure 5, in which the points of the graph are the orientation symbols in O-OFS, and the arcs of the graph are the construction variants of the supports that can make up the device assembly.
Figure 5. Graph of the variants of construction of the supports.

The mathematical model for the graph associated with the set of construction variants of the supports, with the objective function, the cost of the device \( c \), and as constraints: accuracy \( \varepsilon \), productivity \( p \), flexibility \( f \), manufacturing preparation time \( t \) and the behavior in operation \( s \), is of the form:

\[
\begin{align*}
\text{Min} & \quad C = e_{11} x_{11} + e_{12} x_{12} + e_{13} x_{13} + \ldots + e_{33} x_{33} \\
& \quad + e_{11} x_{11} + e_{12} x_{12} + e_{13} x_{13} + e_{14} x_{14} \leq \varepsilon_{1\text{max}} \\
& \quad + p_{11} x_{11} + p_{12} x_{12} + p_{13} x_{13} + p_{14} x_{14} \geq p_{1\text{min}} \\
& \quad + f_{11} x_{11} + f_{12} x_{12} + f_{13} x_{13} + f_{14} x_{14} \geq f_{1\text{min}} \\
& \quad + t_{11} x_{11} + t_{12} x_{12} + t_{13} x_{13} + t_{14} x_{14} \leq t_{1\text{max}} \\
& \quad + e_{11} x_{11} + e_{12} x_{12} + e_{13} x_{13} + e_{14} x_{14} \geq \varepsilon_{1\text{min}} \\
\end{align*}
\]

\[
\begin{align*}
\sum_{j=1}^{5} x_{ij} &= 1; \quad x_{ij} \geq 0; \quad j \in \{1,2,3,4\} \\
& \quad e_{21} x_{21} + e_{22} x_{22} + e_{23} x_{23} \leq \varepsilon_{2\text{max}} \\
& \quad p_{21} x_{21} + p_{22} x_{22} + p_{23} x_{23} \geq p_{2\text{min}} \\
& \quad f_{21} x_{21} + f_{22} x_{22} + f_{23} x_{23} \geq f_{2\text{min}} \\
& \quad t_{21} x_{21} + t_{22} x_{22} + t_{23} x_{23} \leq t_{2\text{max}} \\
& \quad e_{21} x_{21} + e_{22} x_{22} + e_{23} x_{23} \geq \varepsilon_{2\text{min}} \\
\end{align*}
\]

\[
\begin{align*}
\sum_{j=1}^{3} x_{3j} &= 1; \quad x_{3j} \geq 0; \quad j \in \{1,2,3\} \\
& \quad e_{31} x_{31} + e_{32} x_{32} + e_{33} x_{33} \leq e_{3\text{max}} \\
& \quad p_{31} x_{31} + p_{32} x_{32} + p_{33} x_{33} \geq p_{3\text{min}} \\
& \quad f_{31} x_{31} + f_{32} x_{32} + f_{33} x_{33} \geq f_{3\text{min}} \\
& \quad t_{31} x_{31} + t_{32} x_{32} + t_{33} x_{33} \leq t_{3\text{max}} \\
& \quad e_{31} x_{31} + e_{32} x_{32} + e_{33} x_{33} \geq e_{3\text{min}} \\
\end{align*}
\]

\[
\begin{align*}
\sum_{j=1}^{3} x_{3j} &= 1; \quad x_{3j} \geq 0; \quad j \in \{1,2,3\} \\
\end{align*}
\]
Values for orientation errors ($\varepsilon_{11}, \varepsilon_{12}, \ldots, \varepsilon_{33}, \varepsilon_{\text{max}}$), the productivity of the support ($p_{11}, p_{12}, \ldots, p_{33}, p_{\text{min}}$), manufacturing adaptation time ($t_{11}, t_{12}, \ldots, t_{33}, t_{\text{max}}$), operating behavior ($e_{11}, e_{12}, \ldots, e_{33}, e_{\text{min}}$), and the cost of execution and repairs ($c_{11}, c_{12}, \ldots, c_{33}$), will be determined with the computational relations in the paper [1, 9, 11, 12] and introduced into the system of inaccuracies of the mathematical model from equation (22).

The mathematical model written in the matrix form is:

$$
\begin{align*}
&\mathbf{A}^+ \mathbf{X} = \mathbf{U} \\
&\mathbf{A}^+ (\mathbf{\varepsilon X}) \leq \varepsilon_{\text{max}} \\
&\mathbf{A}^+ (\mathbf{p X}) \geq p_{\text{min}} \\
&\mathbf{A}^+ (\mathbf{f X}) \geq f_{\text{min}} \\
&\mathbf{A}^+ (\mathbf{t X}) \leq t_{\text{max}} \\
&\mathbf{A}^+ (\mathbf{e X}) \geq e_{\text{min}} \\
&\text{Min}(\mathbf{C X})
\end{align*}
$$

where:
- $\mathbf{A}$ is the incidence matrix associated with the graph;
- $\mathbf{A}^+$ is the positive side of the incidence matrix;
- $\mathbf{X}$ is the column vector of the construction variants;
- $\mathbf{U}$ is the column matrix with $n$ elements equal to 1: $\mathbf{U} = [1, 1, 1]^t$

After solving the mathematical model, the optimal version of the device construction $\text{VOC}_D$ is composed of the following structures:

$$
\text{VOC}_D = (x_{14}, x_{23}, x_{31})
$$

6. Establishing the optimal construction variant of the processing equipment at the technological process level

When it is desired to evaluate and establish the types of structures of the processing equipment for the entire theological process, the optimization stage $\text{E04}$ is proposed, in which various variants of construction of the devices for orientation and fixing of the semi-finished, transfer, tooling or intended devices are analyzed or the modernization of machine-tools ($\text{VOCET}$).

7. Device construction

The device for orientation and fixing, in figure 6, of the $\text{Tie Rod Body}$, constructed from the optimal structures established by $\text{VOC}_D$, is of rotary type, with four work stations and hydraulic drive, which ensures a high level of accuracy and productivity.

The work piece must be oriented on the support 23 with plan head, short moving prism 12, under the action of the spring 36, with self-centering and locking, oscillating support 11 with flat head and moving ring 24, under the action of the spring 32, with self-centering and locking. The movable elements are sealed by felt gaskets 25, 41 retained by cover 27 and by screws 26, 40.

The fixing is done with a system composed of the clamp L, 19 operated by a hydraulic motor, the oscillating clamp 16 and the oscillating pillars with flat head 13 with self-sealing, retained by the traction springs 14, which ensure a gradual and balanced tightening on the supports without causing stresses and deformations. At the end of the fastening phase, the hydraulic system controls the locking of the movable elements 12 and 24 by means of the pistons, which move in the cylinders of the hydraulic motors 6 and 30 with simple action.

The body of the device 35 with four workstations is assembled on the rotary supports 39, which bring the blank in an upright position for a new processing phase.
The construction of this device with a precise and secure orientation and fixing system, with several workstations and a kinematics adapted to the technological requirements, offers a high level of precision, productivity and flexibility to the technological equipment.

8. Conclusions
The processing methods, the technological process, the algorithm of design-optimization of the structures and the constructive solution of the device with multiple stations, presented in this work, have obvious elements of novelty, which can be developed and adapted for the modernization of the machine tools and the manufacturing system.

In perspective, this type of multiple station rotary device can also be manufactured in a modular variant, such as a combination of two multifunctional components and a hydraulic fastening system that can be conveniently configured according to the type of operation and machine-tools.

This simultaneous-successive approach, as an optimization method, allows the choice of the best solutions as processing procedures, for certain characteristics of the technological equipment, but also offers the possibility of making new processing equipment with characteristics and performances superior to the existing ones.

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