METHOD OF OPTIMIZING THE CONSTRUCTION OF MACHINING, ASSEMBLY AND CONTROL DEVICES

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Abstract. Industry dynamics, driven by economic and social requirements, must generate more interest in technological optimization, capable of ensuring a steady development of advanced technical means to equip machining processes. For these reasons, the development of tools, devices, work equipment and control, as well as the modernization of machine tools, is the certain solution to modernize production systems that require considerable time and effort. This type of approach is also related to our theoretical, experimental and industrial applications of recent years, presented in this paper, which have as main objectives the elaboration and use of mathematical models, new calculation methods, optimization algorithms, new processing and control methods, as well as some structures for the construction and configuration of technological equipment with a high level of performance and substantially reduced costs.

1. Introduction

Modern engineering methods and strategies require a permanent analysis of the machining phase from the moment the product is conceived and then at all stages of its existence.

The current trend in the field of machines construction's technology [1-4] promotes a new concept of multi-criteria optimization of manufacturing processes and equipment based on associated importance criteria, prioritized according to the objectives pursued.

The systemic approach to optimizing problems in the field of technological engineering is determined by the need to highlight the multitude of factors that influence it and their interdependencies.

The modernization of the manufacturing processes necessarily implies the development and evolution of the technological equipment for machining, assembly and control, through the development of new solutions in the field of orientation and fixing devices of workpiece [5-10].

In a previous paper [11], there was established a method to optimize the orientation and fixing system of workpieces for the construction of devices, which is a theoretical study on the generating and quotation bases for a particular technological operation.

The present paper is a continuation of the above-mentioned one, which proposes an organological study of constructive structures to establish the optimal solution for the construction, configuration and operation of devices.

2. Methodology to optimize structures for the construction of machining, assembly and control devices

Under current conditions the manufacture of a new product involves the design, execution and approval of technological equipment, especially of devices, at a very fast pace, so that the time and expenses for
the technological preparation of the machining should be as small as possible, but to ensure the level of technical and economical performance imposed.

For machining and control devices, specialized papers [1,11,13] present the methodology to establish the optimal orientation and fixing scheme (SOF-O) expressed by information symbolization of the supports of the orientation and fixing system of the device.

The evolution of machining systems and technological equipment determined a multitude of constructive variants of devices that do not have total correspondence in the information symbolization, and for the analysis of technically possible orientation variants (VO-TP), only the orientation errors in the contact area between the workpiece and support were considered, without taking into account the errors caused by the elements of construction and operation of the support.

2.1. The design-optimization algorithm for the construction of orientation and fixing devices for workpiece

For a more rigorous assessment of the orientation errors in relation to the required machining or control precision and the establishment of rational technical solutions based on the calculation method for the errors of the construction orientation [3], there is proposed a design-optimization algorithm for the construction of the devices shown in Figure 1, following stages:

- E01 – Knowing or determining SOF-O;
- E02 – Coding construction variants of supports associated SOF-O;
- E03 – Establishing the optimizing technical criterion;
- E04 – Establishing the optimizing economical criterion;
- E05 – Defining the optimizing method;
- E06 – Formulating the centralizing table of variants and criteria analyzed;
- E07 – Selecting the structure variants for the construction of supports;
- E08 – Establishing the optimal variant to construct the device.

![Figure 1. Algorithm to design-optimize devices](image)

2.2. Optimizing the construction of devices for machining, assembly and control operations

Devices, as subsystems of the technological system, in the general context of the development and diversification of machines, tools, workpiece and drives, are made in a multitude of constructive variants, which create difficulties in their study and improvement.

For these reasons, the general design-optimization algorithm of the construction of devices with the eight stages of work was established.

**E01 – Knowing or determining SOF-O**

Initially, the quotas and conditions imposed on the analyzed operation or the optimal orientation and fixing scheme (SOF-O) are known as a combination of graphical signs in the information symbolization of the bases of orientation and fixing of the workpiece.

\[
\text{SOF-O} = f(S_{Io}, S_{If})
\]

where,

- SOF-O – optimal orientation and fixing scheme for processing, assembly and control operations;
- \( S_{Io} \) – information symbolization associated to the orientation and fixing bases and supports of device;
- \( S_{If} \) – information symbolization associated to the orientation and fixing bases and clamping elements of the device.

**E02 Coding the construction variants of the orientation and fixing elements of the device**
Constructive variants for structures, which are known, are defined and coded for each symbol element of the quotation bases BCI, BCII, BCIII, and fixing bases BFIV, BFV of the optimal orientation and fixing scheme set forth in [1], or new constructive variants to be achieved later can also be analyzed.

**System of main orientation supports:**
For BCI–SI OI, structure variants are noted with \( X_{ij} \), where \( i = 1, \ldots, m; j = 1, \ldots, n \),
\( m \) – is the number corresponding to the quotation and fixing bases BCI, ..., BFV;
\( n \) – is the number of structure variants associated to each quotation and fixing base BCI, ..., BFV.
In this case for BCI the structure variants are between \( X_{11}, \ldots, X_{1n} \).
For BCII–SI OII, structure variants are noted with \( X_{ij} \), where \( i = 2; j = 1, \ldots, n \), meaning \( X_{21}, \ldots, X_{2n} \) where \( n \) is the number of structures associated to symbol of quotation base BCII.
For BCIII–SI OIII, structure variants are noted with \( X_{ij} \), where \( i = 3; j = 1 \ldots n \), meaning \( X_{31}, \ldots, X_{3n} \), where \( n \) is the number of structures associated to symbol of quotation base BCIII.

**Fixing system with additional supports:**
For BFIV–SI IV, structure variants are noted with \( X_{ij} \), where \( i = 4, j = 1 \ldots n \), meaning \( X_{41}, \ldots, X_{4n} \) where \( n \) is the number of structures associated to symbol of fixing base BFIV.
For BFV–SI IV, structure variants are noted with \( X_{ij} \), where \( i = 5, j = 1 \ldots n \), meaning \( X_{51}, \ldots, X_{5n} \), where \( n \) is the number of structures associated to symbol of fixing base BFV.

**E03 – Establishing the technical optimizing criterion**
For any construction, the most important technical selection criterion must be precision, which becomes eliminatory and requires the technically acceptable construction solution (SC-TA) to meet condition \( \varepsilon_{c.s} < \varepsilon_{ad.s} \), where:

- \( \varepsilon_{c.s} \) - orientation-positioning error of the construction structure;
- \( \varepsilon_{ad.s} \) - admissible orientation-positioning error of the structure.

These two types of errors are calculated with the relations presented in the works [3,11] and are introduced in the centralizing table of variants and criteria of optimization.

For BCI and SI OI, the established variants of constructive structures \( X_{ij} \) are analyzed as precision through the calculation of admissible orientation-positioning error of the structure \( \varepsilon_{ad.s} \), and of orientation-positioning errors of the structure construction \( \varepsilon_{c.s} \).

Value \( \varepsilon_{ad.s} \) is obtained from relation:

\[
\varepsilon_i = \sqrt{\varepsilon_o^2 + \varepsilon_f^2 + \varepsilon_d^2} \tag{2}
\]

presented in [4], where:

- \( \varepsilon_i \) – installation (positioning) error;
- \( \varepsilon_o \) – orientation error;
- \( \varepsilon_f \) – fixing error;
- \( \varepsilon_d \) – error connected to the device construction.

Formula (2) is true if the three errors are orthogonal or they fulfill normal (Gaussian) distributions.

In the case of machining devices \( \varepsilon_{iad} = \left( \frac{1}{2} \ldots \frac{1}{3} \right) T_p \), where \( T_p \) – is the tolerance of the part at the quotation or condition analyzed.

For the construction of control devices \( \varepsilon_{iad} = \left( \frac{1}{5} \ldots \frac{1}{10} \right) T_p \)

The precision condition is \( \varepsilon_i \leq \varepsilon_{iad} \)

From relation (2), the maximum value of error of the device construction is:

\[
\varepsilon_{dmax} = \sqrt{\left( \frac{1}{2} \ldots \frac{1}{3} \right)^2 T_p^2 - (\varepsilon_o^2 + \varepsilon_f^2)} \tag{3}
\]
\[ \varepsilon_{\text{dmax}} = \sqrt{\left(\frac{1}{10} \ldots \frac{1}{10}\right)^2 T_p^2 - \left(\varepsilon_0^2 + \varepsilon_f^2\right)} , \text{ for control devices} \quad (4) \]

Finally, it can be written:
\[ \varepsilon_{\text{d.ad.}} = \varepsilon_{\text{dmax}} \quad (5) \]

Value \( \varepsilon_{\text{d.ad.}} \), is obtained from the analysis of errors produced by the construction and operation of elements composing each structure of variants with \( X_{ij} \) coded supports.

The calculated values of \( \varepsilon_{\text{c,ad.}} \) and \( \varepsilon_{\text{d.ad.}} \) are actual values introduced in Table 1 for variant \( X_{ij} \).

Proceed similarly for BCII and SI0II, BCIII and SI0III, BFIV and SI0IV, BFV and SI0V, calculate \( \varepsilon_{\text{c,ad.}} \) and \( \varepsilon_{\text{c,ad.}} \) for each variant of structures \( X_{ij} \), then introduce in Table 1.

**E04 – Establishing economical optimization criteria**

Establish the economical optimization criteria \( CE_1, CE_2, ..., CE_6 \), representative of the construction of the devices \[ 3,11 \].

For the simplification of calculations, there are chosen only two economical selection criteria, cost \( (CE_3) \) and flexibility \( (CE_6) \), the actual values of these criteria are determined with relations from \[ 13 \] and are introduced in Table 1.

**E05 – Defining the optimization method**

In order to determine the optimal solution of the variants of structures designed for the construction of the device, the global utility method \[ 14 \] was customized for the analyzed case with the following stages:

- choose a variance interval \( \{0, ..., 1\} \), considered utility, denoted by \( u(v_i) \);
- the most favourable decisional consequence has value 1, noted with \( u(v_i) = 1 \), and the most unfavourable consequence has value zero, \( u(v_i) = 0 \);
- the other utilities will be calculated in stage E06 by linear interpolation with relation:
\[ u_{ij} = \frac{a_{ij} - a_i^0}{a_i^1 - a_i^0} \]
\[ (6) \]

where:
- \( u_{ij} \) – utility of consequence i following criterion j;
- \( a_{ij} \) – value of consequence i following criterion j;
- \( a_i^0 \) – value of the most unfavourable consequence of criterion j;
- \( a_i^1 \) – value of the most favourable consequence of criterion j.

This simple method makes it possible to optimize under certainty conditions and can be used in situations where decision criteria are equally important or decision criteria have different coefficients:
\[ u_g(v_i) = \Sigma u_{ij} \cdot k_j u_{ij} , \]
\[ (7) \]

where \( u_g(v_i) \) global utility, and \( k_j \) is the coefficient of importance of criterion j.

**E06 – Formulating the centralizing table of constructive variants and optimization criteria**

Table 1 centralizing the variants and optimization criteria with encoded variants \( X_{ij} \) of groups of structures BCI, ..., BFV, the optimization criteria (precision - \( C_{pr} \), costs \( C_{c} \), CE1, flexibility \( C_{f} \), CE6, ...), with their actual, admissible and critical value of coefficients of importance (CI) depending on how a variant is related to the criterion analyzed.

In case the interest is different for the decision criteria assign to each criterion a correction coefficient (priority) \( k_c \), according to their importance.
Table 1. Centralizing table of constructive variants and optimization criteria

| Nb. | Structure variants for BCI, ..., BFV | Precision criterion \( C_{pr} \) | Economical criteria – CE and Importance coefficients - CE | \( \Sigma CI \) | Decision |
|-----|------------------------------------|---------------------------------|-----------------------------------------------|----------|---------|
|     |                                    | \( \varepsilon_c^{o-p} \), \( \varepsilon_{ad.s}^{o-p} \) | SC-TA | Cost criterion \( C_c - CE_3 \) | Flexibility criterion \( C_f - CE_6 \) |          |
| BCI-SI_{III} | Actual values | CI_{pr} | \( k_{c}^{pp} \) | Actual values | \( k_{c}^{c} \) | Actual values | \( k_{c}^{f} \) (Max) | Optimal |
| 1   | \( X_{ij} \) | ... | ... | ... | ... | ... | ... | ... | ... |
|     | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| BCIII-SI_{III} | ... | \( X_{ij} \) | ... | ... | ... | ... | ... | ... | ... |
|     | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| BFV-SIF_{V} | ... | \( X_{ij} \) | ... | ... | ... | ... | ... | ... | ... |
|     | ... | ... | ... | ... | ... | ... | ... | ... | ... |

The actual and admissible values are calculated in E_{03} and E_{04}, and those of the coefficients of importance in this table are calculated for the optimization criteria established.

**Precision criterion \( (C_{pr}) \)**

The value of the coefficients of importance \( (CI_{pr}) \) calculated for the precision criterion associated to optimization with the global utility method assumes the choice of a variation interval, which in the analyzed case can be between \{0, ..., 1\}. The most favourable consequence is assigned value 1 and the most unfavourable consequence value zero. The other utilities will be calculated by interpolation.

Given that \( \varepsilon_c^{o-p} \) is in a reverse relation with the variance of the coefficients of importance \( (CI_{pr}) \), when one increases the other one decrease, a method of calculating by inverse interpolation is proposed with the following stages:

- Establish the value of interval \( (v_i) \) of structure \( X_{ij} \):
  \[
  v_i = \varepsilon_{ad.s}^{o-p} - \varepsilon_c^{o-p} ,
  \]

- Determine the number of intervals \( (n_i) \) of the variation interval for the actual orientation-positioning errors of the structures:
  \[
  n_i = \frac{\varepsilon_{ad.s}^{o-p} - \min_{ad.s} \varepsilon_c^{o-p}}{\varepsilon_{ad.s}^{o-p}} ,
  \]

- Calculate the coefficient of importance of an interval \( (CI_i) \):
  \[
  CI_i = \frac{1}{n_i} ,
  \]

- Determine the number of actual intervals \( (n_{ie}) \) of a structure \( \varepsilon_c^{o-p} \),
  \[
  n_{ie} = \frac{\varepsilon_c^{o-p}}{v_i} ,
  \]

- Establish the value of apparent coefficient of importance \( (CI_a) \) of a structure \( X_{ij} \),
  \[
  CI_a = n_{ie} \cdot CI_i ,
  \]

Because the errors \( \varepsilon_c^{o-p} \) and coefficients of importance \( (CI) \) are in a reverse relation, the value of the coefficient of importance of the precision criterion \( (CI_{pr}) \) is calculated with relation:

\[
CI_{pr} = 1 - CI_a ,
\]
**Cost criterion (Cc-CE3)**
Calculate the actual cost of materials, workmanship and heat treatment or operating costs for each \( X_{ij} \) coded structure and introduce data in Table 1.

**Flexibility criterion (Cf - CE6)**
Assess the degree of flexibility to adjust expressed in time (\( G_{AT} \)) with relation from [6]:
\[
G_{AT} = e^{-(TR/TRO)} ,
\]
(14)

Where:
- \( G_{AT} \) – degree of flexibility to adjust expressed in time;
- \( TR \) – time to re-equip for the analyzed system;
- \( TRO \) – time to re-equip for the comparison system.

For each type of \( X_{ij} \) structure, the degree of flexibility to adjust \( G_{AT(Xij)} \) is calculated as the actual value and introduced in Table 1.

**E07 Selecting the variants to construct the device**
After filling the centralizing Table 1, the establishment of the optimal solution for the construction of the orientation and fixing device of the semi-finished product can be done by two methods.

**Method 1**
Sum up the coefficients of importance of the optimization criteria chosen for each analyzed \( X_{ij} \) variant and introduce them into the \( \Sigma CI \) column, then for each group of structures \( BCI, BCII, ..., BFi \), locally optimal of the structure with the maximum value (max \( \Sigma CI \)) is identified.

The optimal construction variant of the device is a sum of structures identified as locally optimal.

The drawback of this method is that sometimes in the case of structures with insufficient precision there is a risk that they may be economically analyzed and lead to errors.

For this reason a new calculation method is proposed for establishing the optimal solution in which the variants of structures with insufficient precision (\( e_{c, s}^{o-p} > e_{ad, s}^{o-p} \)) are eliminated before the final phase of optimization.

**Method 2**
Write the relations for the quoting and fixing bases \( BCI, BCII, ..., BFi \), as follows:
\[
\begin{align*}
\text{MaxV}_{BCI}[C_{f}^{X_{ij}} \cdot k_{c}^{pr}(C_{f}^{X_{ij}} \cdot k_{c}^{e} + C_{f}^{X_{ij}} \cdot k_{f}^{c})]; ...; C_{pr}^{X_{ij}} \cdot k_{c}^{pr}(C_{e}^{X_{mn}} \cdot k_{c}^{e} + C_{f}^{X_{mn}} \cdot k_{f}^{c})],
\end{align*}
\]
(15)

\[
\begin{align*}
\text{MaxV}_{BCII}[C_{f}^{X_{ij}} \cdot k_{c}^{pr}(C_{f}^{X_{ij}} \cdot k_{c}^{e} + C_{f}^{X_{ij}} \cdot k_{f}^{c})]; ...; C_{pr}^{X_{ij}} \cdot k_{c}^{pr}(C_{e}^{X_{mn}} \cdot k_{c}^{e} + C_{f}^{X_{mn}} \cdot k_{f}^{c})],
\end{align*}
\]
(16)

where:
- \( \text{MaxV}_{BCI} \) - maximum value of coefficients of importance of structure variants for \( BCI; \)
- \( C_{f}^{X_{ij}} \) - coefficients of importance of the precision criterion for the structure variants \( X_{ij}; \)
- \( C_{e}^{X_{ij}} \) - coefficients of importance of the cost criterion for the structure variants \( X_{ij}; \)
- \( C_{f}^{X_{ij}} \) - coefficients of importance of the flexibility criterion for the structure variants \( X_{ij}; \)
- \( k_{c}^{pr} \) - correction coefficient (prioritizing) of the precision criterion;
- \( k_{c}^{e} \) - correction coefficient (prioritizing) of the cost criterion;
- \( k_{c}^{f} \) - correction coefficient (prioritizing) of the flexibility criterion.

Similarly write the calculating relations for \( BCIII, ..., BFi \).

The optimal variant of device construction is a combination of structures which meet the maximum condition of values for \( BCI, BCII, ..., BFi \).
E08 Establishing the optimal construction variant for the orientation and fixing device for workpiece

For method 1 to calculate the optimal variant of device construction, there are established the locally optimal structures with Max $\Sigma CI$ of each group $X_{ij}$ of BCI, BCII, ..., BFi, so the relation is:

$$VOC_1^* = \text{OptimBCI} + \text{OptimBCII} + ... + \text{Optim BFi},$$

(17)

For method 2 to calculate the optimal variant of device construction, relation is:

$$VOC_2^* = \text{MaxVBCI} + \text{MaxVBCII} + ... + \text{MaxVBFi},$$

(18)

3. CONCLUSIONS

The modernization of the manufacturing processes is related to the promotion of new methods to design, implement and approve the technological equipment, firstly, of devices, which will certainly ensure a high level of technical and economical performances.

This paper presents an original approach to the design and optimization method and algorithm of device construction, the tabular formulation for the analysis of constructive variants and performance criteria, the inverse interpolation calculation method to determine the precision importance coefficient and the calculation method to establish the optimal variant of the device construction.

The use of these methods ensures the optimization of the devices for machining, assembly and control and can be applied with the necessary customizations to the construction of other types of devices, machines and machining systems.

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