Developing structures for the construction of the processing equipment - Case study

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Abstract: The evolution of the manufacturing processes requires, as a mandatory condition, to increase the performance of the technological equipment for processing, assembling and control, by promoting new solutions in the field of devices of the semi-finished products, but also by developing special or modular multifunctional components for the modernization of machine tools. This paper proposes a method of optimization of the technological process and equipment, which in the first stage determines, on the basis of a technological chart, the optimal sequence and the number of operations or phases of processing, and in the second step with the global utility method, the optimal combination of special or modular structures, from existing or new ones, is determined for the construction and configuration of a flexible multi-slot machine for simultaneous and successive centring and spherical operation. We believe that the creation of tools, devices for orientation and fixing, tooling, support, guidance, reinforcing and transfer blanks and modernization of machine tools, is an important measure to streamline manufacturing systems involving important material effort. Our theoretical and experimental research and industrial applications in recent years aim to develop new structures, processing systems and equipment with features, performance and especially flexibility, superior to existing ones.

1. Introduction
In the field of machine building technologies, current research promotes a new concept related to the optimization of manufacturing processes and equipment, based on technical-economic selection criteria, whose share is ranked by important objectives.

Specialty literature [1,2] suggests interesting directions for approach to manufacturing systems, considering that modern production requires greater mobility in assimilating new products.

The technological process determines the need to increase the level of SDVs and complex manufacturing processes in order to improve the quality, productivity and flexibility level, as well as a lower cost for their realization.

This paper presents, on a case study and industrial application, a new method of combined optimization of process and technological equipment for processing, assembling and control operations.

2. Methods for process optimization and modernization of technological equipment
Developing characteristics and increasing the performance of technological equipment is possible if, at the stage of development of the technological process, the conditions and functions imposed on
new structures, for the construction and upgrading of tools, orientation and fixing devices, drive and transfer devices, machine-tools and complex processing systems.

2.1. The general design-optimization algorithm for process and technological equipment

For the most rigorous assessment of technical and economic problems and the establishment of rational solutions in the field of manufacturing technologies, in the paper [3] is proposed the three stage, 14 step general processing, assembly, or control algorithm presented in figure 1.

![Figure 1. General algorithm of design-optimization processes and manufacturing equipment.](image)

\[ E_{01} \rightarrow E_{02} \rightarrow E_{03} \rightarrow E_{04} \rightarrow E_{05} \rightarrow E_{06} \rightarrow E_{07} \rightarrow E_{08} \rightarrow E_{09} \rightarrow E_{10} \rightarrow E_{11} \rightarrow E_{12} \rightarrow E_{13} \rightarrow E_{14} \]

\[ N_{01} \rightarrow N_{02} \rightarrow N_{03} \]

2.2. Establish optimal sequence of operations and key features of the technological equipment

\[ N_{01} \rightarrow \text{Process optimization level (POL)} \]

After analysing the technical documentation of the workpiece, the possible technological operations are identified and their optimal sequence is established with the technological chart method.

The operating plan for the analysed part is drawn up and the main characteristics of the tools, devices and equipment that will be assigned to the technological process are defined.

\[ N_{02} \rightarrow \text{Structure optimization level (SOL)} \]

It analyses whether the existing structures ensure the conditions imposed in the technological process, or it will be necessary to develop new structures with characteristics and performances superior to those existing.

\[ N_{03} \rightarrow \text{Optimization of complex technological equipment level (OTEL)} \]

Based on the characteristics of the manufacturing system, the structure of its composition is encoded, the criteria and the optimization method are chosen, after which the optimal construction and configuration of the technological equipment is established from the centralized table and proposed calculations.

E01- Analysis of the technical documentation

For a component in the Car Seat, we present the Headrest Support, made of round steel (laminated bar), regarding the dimensions and conditions imposed on the design drawing from figure 2 and the technological process, if there is any.

E02- Identification of the required operations

The operations (procedures) of the existing technological process have been identified, which ensure the achievement of quotas and conditions according to the documentation, but in the spherical
turning operation the pieces have a clear cut where the cutting speed is zero and require additional adjustment operation, and the productivity of this operation can only be achieved by using 6, SN560x1500 lathes.

In these considerations we have identified and encoded the processing operations for a new technological process like this: x1-op.05, Debiting; x2-op.08, Debiting, variant; x3-op.10, Centering; x4-op.11, Spherical turning; x5-op.12, Centering and spherical turning; x6-op.15, Bending; x7-op.16, Bending, variant; x8-op.20, Recovery; x9-op.25, Milling I; x10-op.30, Milling II; x11-op.35, Adjustment; x12-op.40, Plan bending; x13-op.45, Final control.

E63- Determining the optimal succession of operations
- Explains the column vector X, in relation (1), describing the set of procedures processes originally specified:

\[ X = [x_1 x_2 x_3 ... x_j ... x_{13}] \]  

1

- The components of the vector X are bivalent variables and have the value:

\[ x_j = 1 \text{ or } 0, j \in N = \{1, 2, 3, ..., 13\} \]  

2

When the process is optimal \( x_j = 1 \), and when it is not optimal \( x_j = 0 \).

- Write down with C, the processing cost vector line, in relation (3), for operations encoded with \( x_1, x_2, x_3, ..., x_{13} \).

\[ C = [c_1 c_2 c_3 ... c_j ... c_{13}] \]  

3

- The mathematical model is expressed as in relation (4):

\[
\begin{align*}
\min(C \cdot X) &= \min \left( \sum_{j=1}^{13} c_j x_j \right), j \in N = \{1,2,3,...,13\} \\
F_i(X) \text{ Rel } O, i \in L = \{1,2,3,...,l\}; x_j &= 1 \text{ or } 0
\end{align*}
\]  

4

where: CX is the objective function of the problem; \( F_i(X) \) represent the conditions (restrictions) of the problem; RelO is the relational form operator \( <, =, \geq \).

- For this technological process, the set of processing variants highlighted by the coded operations (procedures) in the matrix X is expressed by the technological graph in figure 3.

The graph nodes represent the moments of transformation of the geometry of the piece, \( M = \{1, 2, 3, ..., 10\} \), and coded operations are the arcs of the graph \( (x_1, x_2, x_3, ..., x_{13}) \).

Insert the A matrix of incidence of the used procedures, with 10 lines and 13 columns, the positive part of which is \( A^+ \), but also the square matrix \( T_c, R_c \) of the tolerances and roughness capable, the linear matrix \( T_p, R_p \) of the precise tolerances and roughness. Write the system of inequities in relation (5) and resolve, respecting the conditions \( \sum x_j = 1, x_j = 1 \text{ or } 0 \).

![Figure 3. Technological graph of processing variants.](image-url)
The optimal variant of the proposed technological process is the combination of procedures (operations) with the sequence shown in relation (6).

\[
\text{VO}_\text{PT} = [x_1, x_6, x_8, x_9, x_{10}, x_{11}, x_{12}, x_{13}]
\]  

(E05 - Preparation of the technological documentation)

An operational plan or a simplified technology sheet shall be drawn up.

(E06 - Characteristics of tools, devices and machines)

The main characteristics of the technological equipment related to the precision of processing, productivity, rigidity, processing direction, the possibility of multislot processing and transfer systems, the processing phases and a high level of adaptability of the structures, as well as of the system.

(N02 - Structure optimization level (SOL))

Based on the optimized technological process presented in relation (6), we have established a new method of processing, able to eliminate the lack of precision of the spherical turning operation, the additional adjustment operation and the five normal lathes, which will be achieved with the help of attached structures on a single lathe SN560X1500.

(E06 - Analysis of existing structures)

An existing structure is analysed that has the functions, characteristics and performance as close as possible to those defined in the step E05.

For this application, we have identified a multifunctional drive device (MDD), previously developed [3,5], which can be attached to a normal lathe instead of a mobile doll or other universal machines or aggregate machines. The choice was made on the basis of the Structure Presentation Sheet and a Table of Data and Features realized in work [6].

(E07 - Developing new structure)

For other equipment in the composition of the processing system, new structures with characteristics and performances superior to existing ones, which will be included in the Presentation Sheet and the Characteristic Table obtained by inventive design methods and techniques [7].

For this purpose, we have developed certain structures for the modernization of a normal lathe, which will be analysed in the following steps, which presents the method of optimization of the complex technological equipment.

(N03 - Optimization of complex technological equipment level (OTEL))

New structures are being developed and machine-tools and complex processing systems are configured.

(E08 - Characteristics of the technological equipment)

The characteristics and performance of the structures are evaluated, according to the requirements imposed on the analysed operations, which, for the multi-axis adjustable head with cardan shafts in figure 4, are shown in a table in the paper [6].

Data and technical solutions have been developed in the papers [5, 8], and some characteristics are calculated with relations from the work [4, 9].
Figure 4. Multi-axis adjustable head with cardan shafts.

**Encoding the structures**

On the basis of the method of processing established in the optimized technological process, the variants of structures that can be attached to the lathe guides and trolley are encoded, in the areas which ensure, from a cinematic and technological point of view, the realization of the processing phases of the centering and spherical turning operation. 12.

Possible variants of structures are noted with $x_{ij}$, where: $i=1,...,m$, represents the number of types of structures ($S_1, S_2, S_3, S_4$) and where they are located; $j=1,...,n$, represents the number of constructive variants of the types of structures ($n = 14$).

For the modernization of the normal lathe, coding the variants of structures is:

- **$S_1$- Tools, in the main spindle (MS)**
  - $x_{11}$- simple tool (turning bar with a profiled knife);
  - $x_{12}$- Turn bar with two profiled knives;
  - $x_{13}$- special multiax head with turned bars and profiled knives;
  - $x_{14}$- multiax adjustable head with cardan shafts and profiled knives.

- **$S_2$- Orientation and fixing device for parts on the lathe carriage**
  - $x_{21}$- orientation and fixing device successive, fixed, with one piece;
  - $x_{22}$- orientation and fixing device successive, fixed, modular, with one piece;
  - $x_{23}$- orientation and fixing device, rotary, special, with a post (one piece);
  - $x_{24}$- orientation and fixing device, rotating, modular, with two posts (2x2 pieces).

- **$S_3$- Drive device (DD), instead of the mobile doll**
  - $x_{31}$- drive device for tools via trapezoidal belts, fixed;
  - $x_{32}$- drive device for tools by gears, fixed;
  - $x_{33}$- work unit movable, hydraulically.

- **$S_4$- Multiaxial heads on the drive device**
  - $x_{41}$- special multiax head with centering tools;
  - $x_{42}$- multiax adjustable head with eccentric centering tools, coaxial with the main spindle (MS);
  - $x_{43}$- eccentric adjustable multiaxial head with centering tools, moved away from the MS.

**Optimization criteria**

For the analysed structures, the most important and relevant optimization criteria are related to precision ($\varepsilon$), productivity ($p$), flexibility ($f$), the manufacturing preparation time ($t$), in-service behaviour ($e$) and cost ($c$) which has the values established with the calculations of the works [9, 10, 11, 12], and presented in table 1.
Table 1. Optimization criteria.

|                | S₁      | S₂      | S₃      | S₄      |
|----------------|---------|---------|---------|---------|
| ε              | 0.065   | 0.025   | 0.026   | 0.029   |
| p              | 1       | 2       | 3.69    | 3.97    |
| f              | 0.352   | 0.623   | 0.367   | 0.985   |
| t              | 0.987   | 0.992   | 0.367   | 0.999   |
| c (€)          | 420     | 470     | 2950    | 1850    |

**E₁₁ - Choosing the optimization method.** We have customized the global utility method presented in the paper [3], in the analysed case, in which the CI coefficients are calculated by interpolation in the range of variation \( [0, ..., 1] \).

**E₁₂ - Centralized table.** Build and complete the centralizing table 2 of the encoded structure variants \( xₖ \) of the types of structures \( S₁, ..., Sₘ \), optimization criteria \( (\varepsilon, p, f, t, e \) and \( c)\), with their actual and admissible values calculated with the relations in the works \([4, 13]\), but also the coefficients of importance \( (CI) \) and correction (ranking) \( k_c \).

To simplify the presentation, only three optimization criteria are completed \((C_{pr} - precision, C_r - flexibility, C_c - the cost)\) and some of the variants of structures \( x_{ij} \).

When the optimization goal is the upgrading of a machine tool, an additional optimization criterion specific to the machine type \( C_{SU}^{s} \) (operation diversity).

Table 2. Centralizing table of constructive variants and optimization criteria.

| Nb. | Structure variants \( x_{k} \) for \( S_1, ..., S_m \) | Precision criteria \( C_{pr} \) Actual values | Technical-economic criteria Actual values | Cost criteria \( C_c \) Actual values | Specific criteria \( C_{SU}^{s} \) Limits (minimum) |
|-----|-----------------------------------------------------|-----------------------------------------------|------------------------------------------|-------------------------------------|-------------------------------------|
| 1   | \( x_{11} \)                                        | \( e_{opt}^{pr} \) 0.065 0.06 CI₁₁k₁¹ 0.352 0.38 1.3 420 1 1.2 0.1 1 |
| 2   | \( x_{12} \)                                        | \( e_{opt}^{pr} \) 0.025 0.06 \( k_1 \) 1.3 470 0.98 1.2 0.3 1 |
| 3   | \( x_{13} \)                                        | \( e_{opt}^{pr} \) 0.029 0.06 0.51 1.7 1850 0.68 1.2 0.9 1 |
| 4   | \( x_{14} \)                                        | \( e_{opt}^{pr} \) 0.017 0.06 0.71 1.7 2100 0.63 1.2 0.3 1 |
| 5   | \( x_{21} \)                                        | \( e_{opt}^{pr} \) 0.022 0.06 0.63 1.7 3200 0.39 1.2 0.4 1 |
| 6   | \( x_{22} \)                                        | \( e_{opt}^{pr} \) 0.024 0.06 0.6 1.3 2792 0.48 1.2 0.8 1 |
| 7   | \( x_{23} \)                                        | \( e_{opt}^{pr} \) 0.016 0.06 0.74 1.3 4500 0.11 1.2 0.8 1 |
| 8   | \( x_{24} \)                                        | \( e_{opt}^{pr} \) 0.021 0.06 0.65 1.3 5000 0.0 1.2 0.8 1 |
| 9   | \( x_{31} \)                                        | \( e_{opt}^{pr} \) 0.026 0.06 0.57 1.3 2950 0.44 1.2 0.3 1 |
| 10  | \( x_{32} \)                                        | \( e_{opt}^{pr} \) 0.038 0.06 0.37 1.3 840 0.91 1.2 0.3 1 |

**E₁₃ - Selecting options**

In order to establish the optimal solution for the construction of the technological equipment, it is proposed the calculation relation (7), presented in the paper \([3, 4]\). To select the analyzed
structure variants, the values in table 2 are replaced and the variant that sums the maximum number of points is identified.

\[
\text{MaxVS}_{1}^{\text{MU}}(0; 1.35; ...; 1.53) \Rightarrow \text{MaxVS}_{1}^{\text{MU}} = 1.53 = x_{14}
\]

Similarly, write the calculation relation (7) and the other types of structures \(S_{2}, S_{3}, S_{4}\) and is obtained:

\[
\text{MaxVS}_{2}^{\text{MU}} = 1.6 = x_{24} ; \quad \text{MaxVS}_{3}^{\text{MU}} = 1.65 = x_{31} ; \quad \text{MaxVS}_{4}^{\text{MU}} = 0.99 = x_{43}
\]

\(E_{14}\) - Establishing the optimal version of the construction of the technological equipment. The optimal variant is a combination of structures that meet the maximum condition in the form shown in relation (8).

\[
\text{VOC}_{\text{ET}} = x_{14} + x_{24} + x_{31} + x_{43}
\]

3. Construction of technological equipment

Structures \(x_{14}, x_{24}, x_{31}, x_{43}\), obtained on the basis of the described optimization methods, allowed the configuration of the complex technological equipment of figure 5, which is a flexible spherical centering and spindle machine, modularly built on the frame of a normal lathe, with certain novelty elements confirmed by the two patents [5, 8] and as an industrial application.

![Figure 5](image-url) Flexible spherical centering and spindle machine.

As a working method, the two pieces oriented and fixed to the two-post (I and II) rotary device 10, travel with the turntable carriage to the right for the centering step performed by the adjustable multiaxial head 7, on the drive device 8, rotates and moves to the left for the spherical turning step, made by the tools 4, of the multi-axis adjustable head 3, followed by retraction, rotation, and the cycle is repeated.
The high level of machining precision is provided by the device orientation and fixation system, the construction and operation of the multiax heads, and the working method in which the two spherical centering and spindle operations are made in the same attachment of the workpieces on transfer system.

Productivity increases greatly due to multiax processing of two pieces simultaneously and overlapping machining times over the clamping-detachment of the workpiece.

The modular construction offers a high level of flexibility as possibilities for re-use of structures but also for very rapid return to the original features of the normal lathe.

4. Conclusions
The combined design-optimization methods and algorithm described are a theoretical original approach as a processing method and structures that configure a specialized tool machine from modular, adjustable and flexible components with high precision and productivity, but also with a low cost.

In the same way, by customizing the presented methodology, new structures can be developed for the construction of tools, devices, systems, complex equipment for processing, assembling or control.

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