The choice of an optimal technological process for mechanical treatment of machine components based on structural models

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Abstract. The article discusses the optimization of a technological process for mechanical treatment of machine components. As a rule, a technological process implies many variants which complicate the mathematical solution of optimization tasks. In this regard, this work suggests considering a multi-variant technological process as a digraph. This method deals with searching all the graph paths and determining graph lengths, associated with the values of different optimization criteria. The article also considers the ways to choose the optimal path (corresponds to an optimal technological process). The detailed description of threshold optimization, as well as generalized criterion optimization methods, is given based on the example of a technological process for nut manufacturing.

1. Introduction
The technological process of mechanical treatment implies many variants. Manufacturing components according to technical requirements and drawings is possible with different processing methods, operating processes, equipment, tools, and instruments [1–23]. Theoretically, all variants lead to obtaining a ready-made component according to the drawing. The optimization of calculations is aimed at choosing the optimal variant of a technological process of treatment in comparison with other variants. This should reduce the time of treatment, its cost and energy consumption, as well as minimize risks and other factors, used in the analysis. These factors are important criteria for optimization.

2. Materials and Methods
The variants of a technological process are usually shown as a digraph where many nodes represent the operations of a technological process, while many graph arcs are logical connections, representing the order of operations. A graph has one entry node and one exit node.

Fig. 1 represent a graph of a technological process for mechanical treatment of some abstract component.

There are the following notations on this graph: The graph nodes are the operations of a technological process, while arcs represent logical connections between operations. The graph starts with one node (node 1 on fig. 1) and ends with one node (node 19 on fig. 1), which may be fictitious. In reality, there may be for example three simultaneous variants for initial operations within a technological process, corresponding to nodes 2, 3, and 4 (fig. 1). In this case, node 1 will be fictitious.
Figure 1. An example of a graph that represents a multi-variant technological process

With one optimization criterion, it is relatively easy to optimize the task of finding the optimal variant. It becomes much harder when two or three criteria are involved simultaneously. There is no rigorous mathematical solution for the task of multi-criterion optimization. For its solution, it is necessary to use special mathematical tools: the decision theory, mathematical programming, etc. Together with formal elements, solving this task requires informal elements, using “common sense”. The role of a subject, making decisions, can be huge. The choice of an optimal variant involves, for example, deciding to what extent you can ignore one factor of a technological process to get a significant gain in another one. This cannot be achieved through formal mathematical dependencies.

The paper aims to analyze the mathematical approaches towards optimization of technological processes, show deficiencies and find more appropriate models. Also, it is supposed to take a wider look at the problem and show the necessity of informal analysis.

Let’s define the concept of “j path length \((j=1,q)\) based on \(k\) optimization criteria” on all the possible graph path \(\{q\}\), connecting the first and last nodes \(L_{jk}\). This is the sum of values of the \(k\) criterion \((k=1,t)\) across all the nodes of the \(j\) path.

The number of graph paths in our example is not big and it is easy to find them by simply searching variants. For the majority of technological processes aimed at manufacturing complex components, the number of graph paths can be much bigger. Thus, there is a problem of determining all the paths and corresponding lengths based on chosen criteria.

To determine all the graph paths, you can use Amacont program (created by A.A. Anferov) [5] or BMAS program (created by B.A. Mitioiglov and A.M. Schipachev) [3]. BMAS is more user-friendly as it has a more comfortable UI. It doesn’t require to convert a graph into a layered representation and is written in Java.

In the list of paths determined for a multi-variant graph, each path has the prime cost value \(C\) and time per piece \(T\). Each path is a particular variant of treatment.

Let’s look at the example which represents the manufacturing of a nut. Figure 2 shows the part of its drawing.
3. Results
Figure 3 shows the graph representing the multi-variant technological process for manufacturing a nut. The values of C and T optimization criteria were calculated for each operation. Let’s examine the variants of the technological process by representing them graphically in C and T criteria coordinates. First, let’s depict this diagram on fig. 4 with absolute values of criteria.
As can be seen, we have some point cloud. To further use and compare the values of criteria, we need to represent them in a relative form. Let’s calculate the lengths of all $q$ paths for each $k$ criteria in a relative form in fig. 5. For $j$ path:

$$L_{jk}^* = \frac{L_{jk} - L_{\min k}}{L_{\max k} - L_{\min k}},$$

which is represented in fig. 5 with relative values of $C^*$ and $T^*$.

This relative representation of results is the only appropriate form, because:

- the dimensionless view allows us to compare criteria that have different dimensions and perform operations of criteria convolution;
- the range of criteria change in the absolute form can be different, but it should be the same in the relative form with the use of convolution formulas. This is also indicated by R.L. Kini and H. Rayfa [4].

If formula (1) is used, then the range of all criteria change in a relative form is from 0 to 1.

There are several methods to determine the optimal variant of a technological process with several optimization criteria:

1) defining the region of compromises and eliminating inherently unsatisfactory solutions;
2) replacing criteria with limitations and searching in the area set by limitations;
3) reducing the task to include only one criterion and solving it by scalar optimization methods.
Figure 5. The diagram representing the primary cost and time per piece in relative values

This is done through:

a) choosing one criterion from several; b) introducing one measurement unit for all criteria; c) convoluting several criteria in one.

Let’s look at the method of choosing one main criterion from several. It represents the most significant properties of a technical object in study. This method is also known as threshold optimization. The rest of the criteria are replaced with limitations; the threshold values of these criteria.

If the value of a supplementary criterion of some solution is worse than a threshold value, this solution is discarded.

Let’s consider it with the example shown above. We suppose that the main criterion of optimization is primary cost $C^*$, while the supplementary criterion is time per piece $T^*$ (fig. 5).

Let’s designate the threshold value of time per piece as $T_{th}$ and assume that it’s equal to 0.1. In this case, the optimal solution will correspond to the point which has a minimum coordinate value along axis $C^*$ inside the area, limited by coordinates and the right line $T^*$=0.1 (fig. 5).

Let’s look at criteria convolution method or in other words generalized criterion optimization.

The formal used to determine a generalized criterion is:

$$ L^*_{o\hat{o}j} = \alpha_C L^* C_j + \alpha_T L^* T_j $$

for this example.

For the general case it is:

$$ L^*_{o\hat{o}j} = \sum_{k=1}^{m} \alpha_k L^* k_j, $$

(2)

where $\alpha_k$ is a weighting factor of $k$ criterion.
For weighting factors, there is equality \( \sum \alpha_k = 0 \). The values of weighting factors are chosen depending on the importance of a criterion.

The data of criterial values of nodes representing operations (as well as data for calculations in a program) should be used in the absolute form. The relative form can be obtained only with the formula (1). The generalized criterion can be calculated using the formula (2) i.e. through the lengths of paths. Generally, we tend to minimize the values of optimization criteria i.e. optimum is minimum. If you need to maximize it, you should take its inverse value, e.g. performance is a reverse value of treatment time.

In our case if we use the method of criteria convolution or finding a generalized criterion in a discrete task definition, the optimal path is found using the following formula:

\[
L_{об, opt} = \min \{L_{об, j}\}
\]

For other criteria the graphical representation is possible. We can find the objective function represented by a straight line, the inclination of which in respect to the axes is set by weighting factors. Next, we will find the direction of its minimization on the diagram and then by means of a parallel shift, we will determine the limit point of intersection with the discrete set, corresponding to the optimal solution (fig. 5).

It is possible to impose other non-formal, subjective limitations (absence of equipment, skills, etc.).

4. Conclusions

The structural analysis of a technological process consists of:
- representing the structure of a multi-variant technological process as a digraph;
- determining the criteria for technological process optimization;
- analytical definition of a generalized criterion by means of an appropriate method.

This analysis helps find the optimal variant of a technological process using several optimization criteria.

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