Information model of multipass mechanical treatment

Ju L. Tchigirinsky* and N V Chigirinskaya
Volgograd State Technical University

* Julio-Tchigirinsky@yandex.ru

Abstract. The applicability of a multidimensional information array describing a phased change in the state of a product during mechanical processing is justified for building information support for CAD / CAM automation subsystems. A mathematical data model has been developed for a formalized solution to the problem of the formed simple technological processing routes for surface treatment in the case of using complex quality indicators that determine the operational properties of products.

1. Introduction
Problems of design of route technology of machining are always reduced to the solution of a problem of the guaranteed maintenance of requirements of accuracy and quality of the product set in design documentation. Until recently [1], [2] most of the working drawings of engineering products contained mandatory requirements for dimensional accuracy, permissible errors of shape and mutual arrangement of surfaces and permissible microgeometric, most often high-altitude, microprelief parameters.

Modern machine-building production should be focused primarily on ensuring the required performance properties of individual parts and products as a whole. Performance properties of the product are determined [2] by a set of indicators, including, in addition to geometric and microgeometric, also physical and mechanical characteristics of the surface layer. Recently, the production design documentation defines the requirements to ensure the maximum depth of the surface layer with altered physical and mechanical properties (or, otherwise, the defective layer), less often – the sign and the level of residual stresses, in addition to the traditional height microgeometric parameters ($R_a$ or $R_z$), the height ($R_{max}$) and step ($S, S_m, t_p$) parameters and the direction of roughness are additionally normalized. The expansion of the range of regulated product quality indicators requires the use of information structures that provide the possibility of formalized [3] solutions to technological design problems and allow compact storage of data on the technological capabilities of machining methods.

It should also be noted that the data on the possibilities of processing methods in relation to the achievable quality, given in various reference publications, are significantly heterogeneous [2], [4], [5]. Accordingly, the correctness of the design results of routing technologies to a large extent depends on the applied information support.

2. Two stages of formalization the problem of processing routes design
The solution of the problem of formalization and subsequent algorithmization of the generate of processing plans is carried out in two stages: firstly, the assessment and possible increase in the
reliability of reference data; and, secondly, the assessment of the difference between the two methods of machining in terms of the formation of the quality of the product.

2.1. Evaluation of the reliability of the source data for route planning.

We define the range of variation \( [2, 4] \) values of any of the considered quality indicators, provided by a certain technological transition – technological tolerance of the processing method, – as a set of intersecting intervals of variation (figure 1) of independent random variables (table 1). We consider the left and right boundaries of the technological tolerance as independent random variables:

\[
X_{\text{min}} \in \left[ X_{\text{min} \text{mid}}, X_{\text{max} \text{mid}} \right], \quad \text{standard deviation } S_{\text{min}}, \quad \text{probability density } F_{\text{min}}(x),
\]

\[
X_{\text{max}} \in \left[ X_{\text{min} \text{mid}}, X_{\text{max} \text{mid}} \right], \quad \text{standard deviation } S_{\text{max}}, \quad \text{probability density } F_{\text{max}}(x).
\]

**Table 1.** The symbols in the formulas and the schematic representation (figure 1).

| Value or range of values | Point or interval in the schematic representation | Symbol in the text and calculation formulas |
|--------------------------|-----------------------------------------------|---------------------------------------------|
| Left border of the bands crossing (the smallest value of the index) | \( a \) | \( X_{\text{min}} \) |
| Average value of the crossing of the left borders of the ranges is the nominal minimum value of the indicator | \( b \) | \( X_{\text{mid}} = X_{\text{min}} \) |
| Largest value of crossing the left boundaries of the ranges | \( c \) | \( X_{\text{max}} = X_{\text{mid}} \) |
| Average value of a random variable | | \( X_{\text{mid}} = \bar{X} \) |
| Smallest value of crossing the right boundaries of the ranges | \( d \) | \( X_{\text{max}} \) |
| Average value of crossing the right borders of the ranges is the conditional maximum value of the indicator | \( e \) | \( X_{\text{mid}} = X_{\text{max}} \) |
| Right border of the bands crossing (the highest value of the indicator) | \( f \) | \( X_{\text{max}} \) |
| Variation of the lowest possible value of the technological indicator | \([a, c]\) | \( F_{\text{min}}(x) = f_1(x, X_{\text{mid}}, S_{\text{min}}) \) |
| Variation of technological parameters | \([b, e]\) | \( F_{\text{mid}}(x) = f_2(x, X_{\text{mid}}, S) \) |
| Variation of the highest possible value of the technological indicator | \([d, f]\) | \( F_{\text{max}}(x) = f_3(x, X_{\text{mid}}, S_{\text{max}}) \) |
The probability density value (1) in the range of variation of the boundaries is determined with accordance the probability multiplication theorem for joint independent events:

\[
F(x) = \begin{cases} 
F^{\min}(x) \cdot F^{\mid}(x) & x \in [a, b] \\
F^{\mid}(x) & x \in [b, e] \\
F^{\max}(x) \cdot F^{\mid}(x) & x \in [e, f] 
\end{cases}
\]  \hspace{1cm} (1)

The calculation [5] shows that the probability of falling into the ultimate intervals \([a; b]\) and \([e; f]\) is negligible, therefore, as a technological tolerance, we take the interval of change in the quality index within \([b; e]\).

2.2. The differences in processing methods evaluation.

The results of the processing plan should be expressed quantitatively in the values of the criteria of accuracy and quality of the product, first, and evaluated in terms of reliability, second. In fact, to build a sequence of surface treatment, it is necessary to choose in the accuracy tables «interfacing» processing methods, quantitative characteristics of which differ significantly. As a criterion of difference, we use the variation coefficient [4], [5] the difference between the mean values of random variables corresponding to the processing quality of «interfacing» technological transitions. The reliability at each stage of the technological route, as well as the reliability of the processing plan as a whole, is estimated [5] using the integral membership function (2, figure 2).

\[
\Phi(V) = 2 \cdot \min \left( \begin{array}{c}
\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{V^{-2}} e^{-0.5V^{-2}} dV \\
0.5 + \frac{1}{V^6} + \frac{1}{12 \cdot V^2} \\
0.5 + \frac{1}{2 \cdot V^3}
\end{array} \right) - 1 
\]  \hspace{1cm} (2)

where \(V\) – variation coefficient value.

This calculation allows you to make an assessment of the software, so called, «pessimistic forecast» – to estimate the minimum possible probability of differences in technological tolerances of two interfacing processing methods, i.e., in fact, the significance of changes as a result of the technological transition, the quality indicator under consideration.

Technological methods can be considered similar when the variation coefficient is less than 0.17 [5]. Each of the considered pairs of processing methods is characterized by its own value of changes in the accuracy and quality of processing. The organization of data in the form of a usual "flat" table does not allow to reflect these features in the information array. As a basis for constructing a logical model of the directory, we consider the «adjacency matrix» used to describe networks and graphs in discrete mathematics.
Figure 2. Significance of the changes of quality processing criterion

On the example of the arithmetic mean deviation of the microrelief (Ra), we show an example of an information structure that displays (figure 3) the technological tolerances for each processing method, the value of the change in the quality index in the sequential execution of any pair of processing methods and an assessment of the reliability of this change.

Figure 3. The layer of the probability table accuracy (example)

The reliability of the indicator change can be to estimate by the value of the cumulative probability (2). The estimation of changes in the accuracy index is depending on the nature of the corresponding random variable:

- the difference of values for a discrete random variable resulting from the classification of direct measurements. A discrete quantity is, for example, a precision quality;
- the ratio of values for a continuous random variable obtained from direct measurements. For example, any microprofile parameters of the treated surface can be to considered as a continuous values.

3. Probabilistic accuracy tables

Multidimensional data array, each plane «cross-section» (layer) containing the above-mentioned information – the magnitude of change and the reliability of change index of quality in all sequential pairs of processing methods, a single measure of quality is called [3] a «probabilistic accuracy table». The probabilistic accuracy table is an analogue of the adjacency matrix of a directed graph and, therefore, can be to considered as an information basis for a formalized search for options for constructing machining sequences.
Taking as a basis the need for a constant significant improvement in the quality of the workpiece during each subsequent machining transition, you can build:

- acceptable technological routes – it is enough to consider all the pairs of combinations of processing methods. Such a formal solution to the problem of route design initially does not make sense, since it may contain pairs of adjacent technological transitions that do not change, in some cases, impairing the quality;
- permissible rational technological routes – for this purpose it is necessary to include in the sequence only those adjacent pairs of transitions for which the value of reliability of change of the quality index exceeds the threshold value determined in advance, – confidence probability;
- optimal technological routes – in addition to taking into account the reliability of the change in the quality index, the «weight» characteristic of a pair of adjacent technological transitions should be taken into account.

4. Information model of multipass mechanical treatment

The information structure described above – a probabilistic accuracy table containing several «layers» – allows you to design a multi-pass sequence of surface treatment, the quality of which is set by a single criterion. In practice, the quality is rationed by at least two [1], [2], and in the production of responsible products – and more quality indicators.

Probabilistic accuracy table is a three-dimensional information structure:

1) each layer of the probabilistic table contains data for one of the parameters of the considered technological quality indicator – characteristic values that are achievable at each stage of processing when performing a pair of adjacent technological transitions; probabilistic assessment of the reliability of changes these values; to solve the optimization problem – the values of «costs» (optimization criterion) at the characteristic points of the processing route;
2) by rows – data related to the last performed technological transition;
3) by columns – data related to the previous technological transition.

To solve the problem of guaranteed quality assurance, normalized by a set of indicators, it is necessary to consider a set of several – by the number of quality indicators, – probabilistic tables. Therefore, the model of such technological route should be a four-dimensional information structure – so-called, hypercube.

It is known that the problem of finding rational paths in a multidimensional network is of great computational complexity. To solve this problem, we perform a step-by-step transformation of the information hypercube to the form of an adjacency matrix of an oriented unweighted graph (digraph), logically describing the possibility of simultaneous implementation of a complex of technological quality indicators.

- We transform each individual probability table, taking into account the confidence probability of a technological indicator change, into the adjacency matrix of the digraph (table 2). Reliable values of changes in technological parameters replace by ones, false – by zeros.
- Perform multiplication (3) of the elements in the corresponding rows-columns of the considered adjacency matrices;

\[ A_{ij} = \prod_{s=1}^{n} a_{ij}^s; \]

here the lower indices \( i, j \) define rows and columns (the next and the previous technological transitions) of the adjacency matrices of the corresponding hypercube layers; the upper index \( s \) – the layer number; \( n \) – the number of layers (rationed quality indicators).
Table 2. Example of transformation the layer of probabilistic table into an digraph adjacency matrix.

| Previous technological transitions | Variation coefficient | Adjacency matrix |
|-----------------------------------|-----------------------|-------------------|
|                                   | Next transitions      | Next transitions  |
|                                   | 1  2 3 4 5            | 1  2 3 4 5       |
| 1 Roughing turning                | 0,17 0,19 0,07 0,08   | 1 1 0 0          |
| 2 Semi-finishing turning          | 1,0  2,69 0,15 0,15   | 0 0 0            |
| 3 Single turning                  | 1,0  0,45 0,18 0,18   | 1 1 1            |
| 4 Semi-finishing grinding         | 0 0 1,0 1,12          |                  |
| 5 Finishing turning               | 0 0 1,0 0,51          |                  |

- The resulting adjacency matrix \( (A) \) describes an unweighted digraph of processing that includes \( (A = 1) \) connecting such pairs of technological transitions, the sequential execution of which in the route guarantees the required processing quality for a set of rationed indicators with a probability is not lower than \( \delta^S \), where \( \delta \) – confidence probability.
- It is possible to use [3] known algorithms of discrete mathematics to find a set of rational processing routes.

After determining the set of rational routes, you can «return» to the actual quantitative weight characteristics of the digraph of processing and perform cost calculations and optimization only for a limited set of rational solutions.

5. Conclusion
The formation of a set of indicators of the quality of the unit surface can be mathematically described by the weighed digraph, in which each node is set by a set of characteristics of the accuracy of dimensions, surface condition and other parameters that determine the state of the product at the appropriate time.

The description of technology of processing products in the form of the weighed digraph is possible with the use of information hypercube - multidimensional probabilistic accuracy tables.

To reduce the computational cost, it is acceptable to use the method of phased transformation of the hypercube to the adjacency matrix of the digraph, logically describing the possibility of simultaneous implementation of a complex of technological quality indicators.

References
[1] Safonov S V, Smolentcev V P and Zolotarev V V 2016 Scientific basis of product quality management by modifying the surface layer of materials. High technologies at the present stage of mechanical engineering development (TM-2016) : Proceedings of the VIII Int. scientific and technical conf. (Moskow, May, 19-21, 2016) (Moskow: Moskow Automobile and Road Construction State Technical University) pp 201-204
[2] Suslov A G 2008 Surface engineering of parts : tutorial (Moskow : Publishing house “Mashinostroenie”) pp 320 Access mode : http://www.iprbookshop.ru/5141.html – ELS «IPBooks»
[3] Tchigirinsky Ju L 2018 Technological route designing based with mathematical methods. Naukoemkie tekhnomii v mashinostroenii (High technologies in mechanical engineering). – no 4 (82) pp 13-20
[4] Kheifets M, Gretsky N and Prement G 2019 Technological succession of quality operation parameters in life cycle of internal combustion engine parts. Naukoemkie tekhnomii v mashinostroenii (High technologies in mechanical engineering) no 7 (97) pp 35-42 DOI: 10.30987/article_5c7bd2fec77a9.13115279
[5] Chigirinskii Yu L 2010 Reliability of handbook data in technological design / Yu. L. Chigirinskii .Russian Engineering Research vol 30 no 8 pp 835-837