ISSN 1561-8358 (print)
ISSN 2524-244X (online)

МАШИНОСТРОЕНИЕ, МЕХАНИКА

MECHANICAL ENGINEERING, MECHANICS

UDC 621.9.06+536.75
https://doi.org/10.29235/1561-8358-2020-65-4-422-432

Received 06.08.2020
Поступила в редакцию 06.08.2020

Boris M. Bazrov[1], Mikhail L. Kheifetz[2], Valery L. Hurevich[3], Nikolay N. Popok[4]

[1]Mechanical Engineering Research Institute of the Russian Academy of Sciences, Moscow, Russian Federation
[2]Institute of Applied Physics of National Academy of Sciences of Belarus, Minsk, Republic Belarus
[3]Belarussian State Institute of Metrology, Minsk, Republic Belarus
[4]Polotsk State University, Novopolotsk, Republic Belarus

ASSESSMENT OF PRODUCTION MANUFACTURABILITY OF THE DESIGN IN THE PRODUCT LIFE CYCLE

Abstract. On the basis of technical and economic analysis of the properties of relations between design and technological solutions, a method for the integral assessment of production manufacturability by combining individual manufacturability coefficients at different stages of the product life cycle is suggested. Separate coefficients take into account the influence degree of various constituent stages on the labor intensity of production and maintenance, repair and disposal of the product structure. Design and technological solutions in design systems imply the use of properties such as reflexivity, symmetry and transitivity. As a result, it is proposed to understand the properties set of the product design that determine its adaptability to achieve optimal costs in production and disposal for specified quality indicators and work conditions. A list of manufacturability coefficients of manufacturing a product design has been determined, including coefficients of purchase, repeatability of details and connections, material hardness, borrowing, typing, precision, roughness, mass. An examination of the effectiveness assessment the use tools, equipment and other objects of the technological environment at the stages design and technological production preparation is formalized. The examination includes an analysis of the frequency and duration of the meeting of structural parts elements and the tools state at the stages of their manufacture, operation and disposal.

Keywords: production, disposal, design, product, part, manufacturability, coefficient, labor intensity

For citation: Bazrov B. M., Kheifetz M. L., Gurevich V. L., Popok N. N. Assessment of production manufacturability of the design in the product life cycle. *Vestsi Natsyyanal'nai akademii navuk Belarusi. Seryya fizika-technichnych navuk = Proceedings of the National Academy of Sciences of Belarus. Physical-technical series*, 2020, vol. 65, no. 4, pp. 422–432 (in Russian). https://doi.org/10.29235/1561-8358-2020-65-4-422-432

Б. М. Базров[1], М. Л. Хейфец[2], В. Л. Гуревич[3], Н. Н. Попок[4]

[1]Институт машиноведения имени А. А. Благонравова Российской академии наук, Москва, Российская Федерация
[2]Институт прикладной физики Национальной академии наук Беларуси, Минск, Республика Беларусь
[3]Белорусский государственный институт метрологии, Минск, Республика Беларусь
[4]Полоцкий государственный университет, Новополоцк, Республика Беларусь

ОЦЕНКА ПРОИЗВОДСТВЕННОЙ ТЕХНОЛОГИЧНОСТИ КОНСТРУКЦИИ В ЖИЗНЕННОМ ЦИКЛЕ ИЗДЕЛИЯ

Аннотация. На основе технико-экономического анализа свойств отношений конструкторско-технологических решений предложен метод интегральной оценки производственной технологичности путем объединения отдельных коэффициентов технологичности на различных этапах жизненного цикла изделия. Отдельные коэффициенты учитывают степень влияния различных составляющих этапов на трудоемкость производства и обслуживания, ремонта и утилизации конструкции изделия. Конструкторско-технологические решения в системах проектирования предполагают использование таких свойств, как рефлексивность, симметричность и транзитивность. В результате предложено под производственной технологичностью понимать совокупность свойств конструкции изделия, определяющих ее приспособленность к достижению оптимальных затрат при производстве и утилизации для заданных

показателей качества и условий выполнения работ. Определен перечень коэффициентов технологичности изготовления конструкции изделия, включающий коэффициенты покупаемости, повторяемости деталей и соединений, твердости материала, заимствования, типизации, точности, шероховатости, массы. Формализована экспертиза оценки эффективности применения инструментов, средств оснащения и других объектов технологической среды на стадиях конструкторской и технологической подготовки производства. Экспертиза включает анализ частоты и продолжительности встречи конструктивных элементов деталей и состояния инструментов на этапах их изготовления, эксплуатации и утилизации.

Ключевые слова: производство, утилизация, конструкция, изделие, деталь, технологичность, коэффициент, трудоемкость

Для цитирования: Оценка производственной технологичности конструкции в жизненном цикле изделия / Б.М. Базров [и др.] // Вес. Нац. акад. навук Беларусі. Сер. фіз.-тэхн. навук. – 2020. – Т. 65, №4. – С. 422–432. https://doi.org/10.29235/1561-8358-2020-65-4-422-432

Introduction. Determination and assessment of changes in the design of products, in technological and operational processes, in their disposal, as well as cost indicators and quality indicators of machines, taking into account their mutual influence, are hampered by the multi-connected nature of the interactions of the forming and transforming product [1, 2]. To develop a mathematical apparatus for analyzing the technical and economic efficiency of quality indicators and the cost of products, it is necessary to correctly reduce the dimension of the transformation of analyzed properties, which describes the problem [1, 3].

The correct solution to such a problem is facilitated by the replacement of objects set, interacting with the product, by one object – a technological or operational environment with a possible identity of the replacement results [2, 3]. Determination of the characteristics of a multiply connected environment allows, with known results of its interaction with the product, finding rational values of the quality indicators of the product and carrying out the directed formation of the technological environment [3].

To formalize the conditions for the purposeful creation of technological environments, each set of the system components of the same name is described as a set of design and technological solutions (DTS) [3, 4]. This approach allows any environment to be represented as a tuple, each element of which is an element of the corresponding set of DTS [5].

Due to the redundancy of the technological environment in terms of structural composition, it is advisable to use complex process criteria, that summarize the assessment of design and technological solutions by coefficients, that take into account their degree of influence on the technical and economic indicators of processes and their labor intensity, as an objective function instead of specific values of the set of selection criteria (determined by numerical coefficients) [5].

The purpose of the work is to justify the choice and application of an integrated method for assessing the manufacturability of a product design with specified quality parameters, based on the labor intensity of processes at the stages of its life cycle, and the formation of a set of criteria, that generalizes the assessment of design and technological solutions by coefficients that take into account their degree of influence on the technical and economic indicators of processes.

Analysis of the relations properties for the choice of design and technological solutions. We assume that if any two components of the system have at least one common property, then there is a connection between them in terms of common properties. This makes it possible to organize the choice of DTS by equivalence and preference [2]. By equivalence, dissimilar solutions are selected, which in terms of the totality of their properties must correspond to each other. According to preference, solutions are selected from the ones of the same name that have the best values of the required properties.

This approach makes it possible to formalize the conditions for choosing DTS for a specific value of the established selection criterion and makes it possible to choose a solution according to several criteria corresponding to various properties of DTS.

The adoption of DTS in design systems is traditionally based on the analysis of equivalence ($x \equiv y$) and preference (non-strict $x \leqslant y$ or strict $x < y$) of solutions embedded in the knowledge base. Used properties [1, 6]:

reflexivity ($x \equiv x$, $x \leqslant x$ – true; $x < x$ – false);

symmetry ($x \equiv y \Rightarrow y \equiv x$ – true; $x \leqslant y$ and $y \leqslant x \Rightarrow x = y$ – antisymmetric; $x < y$ and $y < x \Rightarrow$ mutually exclusive – asymmetric);

transitivity ($x \equiv y$ and $y \equiv z \Rightarrow x \equiv z$, $x \leqslant y$ and $y \leqslant z \Rightarrow x \leqslant z$, $x < y$ and $y < z \Rightarrow x < z$ – true).

As a result, using the transitivity property, the most preferable of the previous solutions is compared with the new one proposed or selected from the knowledge base in terms of the symmetry properties of the quality parameters.

In the general case, different nonequivalent DTS are most preferable for different quality parameters from the required set of properties. In this case, it is necessary to use the dominant DTS ($x \ll y$), characterized by the properties [1, 6]:

antireflexivity ($x \ll x$ – false);

asymmetry ($x \ll y$ and $y \ll x \Rightarrow$ mutually exclusive);

non-transitivity ($x \ll y$ and $y \ll z \nRightarrow x \ll z$).

In the absence of symmetry and transitivity to determine the dominance of a parameter, it is advisable to apply a synergetic concept using the concept of a mode of a continuous random variable, which is understood as such a value of the parameter at which its distribution density has a maximum [2, 4].

According to the synergetic concept, stable modes adapt to the dominant unstable modes and, as a result, can be excluded. This leads to a sharp reduction in the number of controlled parameters – the degrees of freedom of the technical system. The remaining unstable modes can serve as order parameters that determine production processes [1, 7].

The distributions of the studied quantities, against which the modes appear, are mainly described by the laws [8]:

1) uniform $f(x) = 1/(\mu_1 - \mu_0)$, if $\mu_0 \leqslant x \leqslant \mu_1$;
2) exponential $f(x) = (1/\mu)\exp(-x/\mu)$, if $\mu > 0$, $x > 0$;
3) normal $f(x) = (1/(\sigma\sqrt{2\pi}))\exp(-(x-\mu)^2/(2\sigma^2))$, if $\sigma > 0$, $-\infty < \mu < \infty$, $-\infty < x < \infty$ or other, where μ – the mathematical expectation; μ_0 and μ_1 – restrictions; σ^2 – variance of random variables x.

The Romanovsky's ratio allows judgement of the degree of statistical data correspondence to the chosen distribution law and on the nature of manifestation modes:

$$R = \frac{\lambda_p^2 - k}{\sqrt{2k}},$$

where λ_p^2 – the Pearson's criterion; k – the number of freedom degrees, i.e. the groups number in studied series, calculated (μ, σ, etc.) and used in calculating the theoretical distribution of statistical characteristics.

Statistical analysis of the production system characteristics within the framework of a wide range of applied technologies, equipment and means of equipment allows limitation of the range of objects and processes under consideration. When choosing the restrictions number for objects and processes, it is advisable to consider the conflicting requirements interdependence for the reliability and for flexibility of the production system. Ratio of reliability – stability and flexibility – adaptability can serve as a criterion for making DTS about the rational structure of the production system [9].

Flexibility and reliability in self-organizing systems can be controlled by changing the subsystems number [10]. Each subsystem has deterministic- – well-defined, and fluctuating – scattered outputs.

It grows in proportion to the subsystem number n according to the central limit theorem with the additivity of the total output, while the scattering increases in proportion to the square root $\sqrt{n}$.

These assessments are based on a linear relationship analysis, but in fact the feedback inherent in manufacturing systems leads to even more significant suppression of the characteristics scatter [11].

When justifying the choice of DTS, it is necessary to take into account the cost of forming the parameters of the processing quality and to consider the mechanisms for controlling the technological process [2, 5].

Manufacturability of design and stages of the product life cycle. The manufacturability of a product design (MPD) has a great impact on the efficiency of the product life cycle stages – design, manufacture, operation, disposal (Technique for testing structures for manufacturability and assessing the level of mechanical engineering manufacturability and instrument-making products. Moscow, Publishing House of Standards, 1976. 56 p.). MPD should show how the product is adapted for operation, manufacture and disposal [12–15].

The separation of MPD into operational and production manufacturability is based on the separation of the nature of the work, performed at these stages. If we compare the types of work, performed at the stages of production and disposal, it can be noted that the same technologies are used. For example,

when cutting blanks and disposing of parts, the same technological methods are used; in the manufacture of a product design (PD), in some cases, partial disassembly of the assembled product is carried out, as in the case of product disposal. Therefore, the manufacturability must take into account the processes of production and disposal of the PD.

Operational MPD should take into account not only the work associated with the operation of the PD, but also the installation and repair of the PD.

All this should be reflected in the formulations of the concept of operational and production manufacturability of PD.

According to the standards, MPD is understood as a set of product design properties that determine its adaptability to achieve optimal costs in production, maintenance and repair for given quality indicators, output and work conditions. As can be seen from this wording, it does not meet the requirements of production manufacturability. It should take into account, firstly, the stage of utilization and, secondly, the "volume of output" should be excluded from the wording, since MPD depends on the technology, and not on the volume of the product and, thirdly, it is necessary to exclude maintenance and repairs related to the stage of product operation.

In this regard, the following formulation of production manufacturability is proposed: *production MPD is understood as a set of product design properties that determine its adaptability to achieve optimal costs in production and disposal for specified quality indicators and work conditions.*

Testing of the PD for manufacturability is carried out at all stages of its creation and disposal.

The effectiveness of the process of testing a PD for manufacturability largely depends on the reliability of the assessment of MPD. Assessment of the level of production MPD is carried out at the stages of its design, technological preparation of production, manufacture and disposal.

It is most difficult to assess MPD when the technologies for its manufacture and disposal are unknown. Therefore, at this stage, the assessment of the level of MPD should be made, firstly, not in absolute, but in relative values, i.e. be determined by the degree of influence of PD characteristics on the labor intensity and cost of the product.

Secondly, as characteristics of the PD, only those that are not directly related to the technological processes of manufacturing and disposal of the product, should be taken into account. For example, such characteristics include a variety of elements, contained in PD, which are not directly related to the technological processes of manufacturing the PD, but at the same time affect the complexity of its manufacture. For example, the greater the variety of elements in the PD is, the greater the laboriousness of its manufacture is.

Methods for assessment the manufacturability of product design. Two methods are used for assessment of MPD: assessments in terms of labor intensity and cost of the product and assessment using design manufacturability coefficients.

Using the first method, it is established whether the values of labor intensity and cost of a new product correspond to the specified ones or not. If the values of the labor intensity and cost of the new product turn out to be higher than the specified ones, then the PD must be tested for manufacturability. Tests should begin with those PD characteristics that determine the laboriousness of the manufacture and the product disposal.

The disadvantages of the method for assessment of MPD include the fact that it does not provide information on what PD characteristics affect the labor intensity and the product cost, and to what extent. This leads to an increase in the labor intensity of the testing PD process for manufacturability and largely depends on the subjective.

In contrast to the first method, the second method potentially makes it possible to establish what characteristics of the structure affect the laboriousness of the manufacture and product disposal, and to what extent. This makes it possible to determine with what PD characteristics it is necessary to start improving the PD, in order to increase its manufacturability and the efficiency of manufacturing and product disposal.

The assessment of the industrial MPD level was considered by the second method. The analysis of the manufacturability coefficients showed, that there are no MPD coefficients at the stage of its disposal; the given coefficients are not divided into the stages of operation and manufacturing of the product; they do not cover all the PD characteristics that affect the labor intensity and product disposal and do not reflect the degree of influence of the PD characteristics on the labor intensity of the production and product disposal.

The listed disadvantages do not allow determining the manufacturability coefficients, which have the greatest impact on the labor intensity of manufacturing the PD and thereby identify the PD characteristics with the improvement of which one should start testing the PD for manufacturability.

Thus, for a complete assessment of the production MPD, an integrated approach is required, taking into account the labor intensity of the production and PD disposal.

Comprehensive assessment of labor intensity at the stages of the product life cycle. To solve this problem, the labor intensity of the PD should be considered as the sum of the production labor intensity and the labor intensity of disposal (Figure 1), where L_1 – the labor intensity of the design preparation, L_2 – the labor intensity of the technological preparation of the production, L_3 – the labor intensity of the production, L_4 – the labor intensity of the technological preparation of disposal, L_5 – the labor intensity of disposal;

L_{11} – the labor intensity of design and calculation work, L_{12} – the labor intensity of the working documentation development;

L_{21} – the labor intensity of the manufacturing processes development for the part, L_{22} – the labor intensity of the assembly process development, L_{23} – the labor intensity of the technological equipment development;

L_{31} – the labor intensity of preparatory and final work for the parts manufacture, L_{32} – the labor intensity of technological transitions for the parts manufacture, L_{33} – the labor intensity of auxiliary transitions, L_{34} – the labor intensity of preparatory and final assembly work, L_{35} – the labor intensity of joining parts, L_{36} – the labor intensity of auxiliary transitions for joining parts;

L_{41} – the labor intensity of the technological processes development for disposal, L_{42} – the labor intensity of the development and manufacture of technological equipment;

L_{51} – the labor intensity of preparatory and final works, L_{52} – the labor intensity of technological transitions for the parts disposal, L_{53} – the labor intensity of auxiliary transitions for the parts disposal, L_{54} – the labor intensity of disassembling.

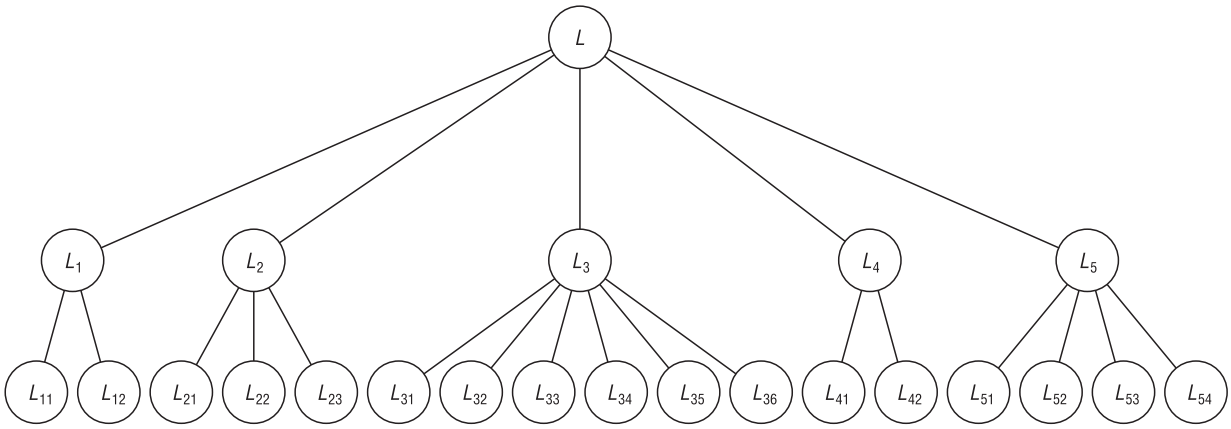

Figure 1. The formation scheme of the full complexity of design, manufacture and disposal product

To establish the coefficients of industrial PD manufacturability at the stages of production and disposal, it is necessary to establish the PD characteristics that affect the labor intensity of the listed types and then establish the degree of their influence.

To solve this problem, we first install the PD elements, the characteristics of which affect the labor intensity of production and disposal.

At the stage of production, we will take parts and their connections as elements, since they determine the complexity of manufacturing. They are divided into purchased, borrowed and original. At the recycling stage, the PD elements are parts, assembly units, connections. All parts and assembly units are divided into defective, recyclable and usable. Suitable parts are divided into: recoverable and not requiring recovery.

After establishing the PD characteristics, their influence on the total labor intensity is determined.

The influence of design characteristics on the labor intensity of technological preparation and products production. Example of the influence of PD characteristics on the labor intensity of production (Table).

On the basis of the data in Table, a coefficients list of manufacturability of PD manufacturing was determined [15, 16] and their calculation formulas were developed.

1. *Purchased coefficient:*

$$C_{\mathrm{P}} = a_2 a_{21} \frac{\sum E_{\mathrm{P}i} b_{\mathrm{com}i}}{E} + a_2 a_{23} \frac{\sum E_{\mathrm{P}i} b_{\mathrm{com}i}}{E} + a_3 a_{31} \frac{\sum E_{\mathrm{P}i} b_{\mathrm{com}i}}{E} + a_3 a_{32} \frac{\sum E_{\mathrm{P}i} b_{\mathrm{com}i}}{E} + a_3 a_{33} \frac{\sum E_{\mathrm{P}i} b_{\mathrm{com}i}}{E},$$

where $E_{\mathrm{P}i}$ – the i-th purchased element; $b_{\mathrm{com}i}$ – the coefficient reflecting the design complexity level influence of the i-th element on manufacture labor intensity; E – the total number of elements in the PD; a_2 – the influence degree L_2 on L; a_3 – the influence degree L_3 on L; a_{21} – the influence degree L_{21} on L_2; a_{23} – the influence degree L_{23} on L_2; a_{31} – the influence degree L_{31} on L_3; a_{32} – the influence degree L_{32} on L_3; a_{33} – the influence degree L_{33} on L_3.

Influence of product design characteristics on labor intensity subspecies

Product design characteristics	Labor intensity specie (L_i)								
	L_2			L_3					
	L_{21}	L_{22}	L_{23}	L_{31}	L_{32}	L_{33}	L_{34}	L_{35}	L_{36}
Amount of purchased elements	+		+	+	+	+			
Amount of repeatable details	+		+	+					
Amount of repeatable connections		+	+				+		
Precision methods		+						+	
Amount of borrowed elements	+		+						
Amount of typical details	+								
Details precision					+				
Surface roughness of details					+				
Material hardness of details					+				
Mass of product elements						+			+
Amount of connection types								+	

N o t e. + – influence of characteristics on labor intensity subspecies.

2. *Repeatable details coefficient:*

$$C_{\mathrm{RD}} = a_2 a_{21} \frac{\sum \left(D_{\mathrm{RD}j} - 1\right)_i b_{\mathrm{RD.com}i} - \sum \left(D_{\mathrm{RD.B}j} - 1\right)_i b_{\mathrm{RD.com}i}}{D - D_{\mathrm{P}} - D_{\mathrm{B}}} + a_2 a_{23} \frac{\sum \left(D_{\mathrm{RD}j} - 1\right) b_{\mathrm{RD.com}i} - \sum \left(D_{\mathrm{RD.B}j} - 1\right)_i b_{\mathrm{RD.com}i}}{D - D_{\mathrm{P}} - D_{\mathrm{B}}} + a_3 a_{31} \frac{\sum \left(D_{\mathrm{RD}j} - 1\right)_i b_{\mathrm{com}i}}{D - D_{\mathrm{P}}},$$

where D – the total number of details; D_{P} – the number of purchased details; $D_{\mathrm{RD}j}$ – the j-th number of repeatable details of the i-th group; $D_{\mathrm{RD.B}j}$ – the j-th number of repeated borrowed details of the i-th group; D_{B} – the number of borrowed details; $b_{\mathrm{RD.com}i}$ – the coefficient taking into account the complexity influence of the design of the i-th repeatable details on the labor intensity.

3. *Repeatable connections coefficient:*

$$C_{\mathrm{RC}} = a_2 a_{22} \frac{\sum \left(C_{\mathrm{RC}j} - 1\right)_i b_{\mathrm{com.c}i}}{C} + a_2 a_{23} \frac{\sum \left(C_{\mathrm{RC}j} - 1\right)_i b_{\mathrm{com.c}i}}{C} + a_3 a_{34} \frac{\sum \left(C_{\mathrm{RC}j} - 1\right)_i b_{\mathrm{com.c}i}}{C},$$

where $C_{\mathrm{RC}j}$ – the j-th number of repeated connections of the i-th group; C – the total number of connections; $b_{\mathrm{com.c}i}$ – the coefficient taking into account the complexity influence of the design of the i-th repeatable connection on the manufacture labor intensity; a_{22} – the influence degree L_{22} on L_2; a_{34} – the influence degree L_{34} on L_3.

4. *Coefficient of details material hardness:*

$$C_{\mathrm{H}} = a_3 a_{32} \left(\frac{\sum D_{\mathrm{H}i} b_{\mathrm{H}i} b_{\mathrm{SH}i}}{D_{\mathrm{H}}} \right),$$

where $D_{\mathrm{H}i}$ – the non-purchased details number of the i-th material hardness value; D_{H} – the total number of details; $b_{\mathrm{H}i}$ – the influence degree of the i-th value of the details material hardness on the manufacture labor intensity; $b_{\mathrm{SH}i}$ – the coefficient of the influence degree of the detail surface areas size on the reduction of the manufacture labor intensity.

5. *Borrowing coefficient:*

$$C_{\mathrm{B}} = a_2 a_{21} \frac{\sum E_{\mathrm{B}i} b_{\mathrm{B.com}i}}{D - D_{\mathrm{P}}} + a_2 a_{23} \frac{\sum D_{\mathrm{B}i} b_{\mathrm{B.com}i}}{D - D_{\mathrm{P}}},$$

where $D_{\mathrm{B}i}$ – the i-th borrowed details; $b_{\mathrm{B.com}i}$ – the coefficient reflecting the design complexity level of the i-th borrowed details on the manufacture labor intensity.

6. *Typification coefficient:*

$$C_{\mathrm{TYP}} = a_2 a_{21} \frac{\sum D_{\mathrm{TYP}i} b_{\mathrm{TYP.com}i}}{D - D_{\mathrm{P}} - D_{\mathrm{B}} - D_{\mathrm{RD}} + m},$$

where $D_{\mathrm{TYP}i}$ – the typical representative of the i-th detail group in TD; D_{RD} – the number of repeatable details; m – the number of repeatable detail groups; $b_{\mathrm{TYP.com}i}$ – the coefficient taking into account the design complexity influence of the i-th type representative on the manufacture labor intensity.

7. *Details precision coefficient:*

$$C_{\mathrm{PR}} = a_3 a_{32} \left(1 - \frac{n}{\sum A_i b_{\mathrm{PR}i} b_{\mathrm{PRS}i}} \right),$$

where A_i – the most rigid i-th accuracy grade, which is chosen between the accuracy grade assigned to the surface size, to its shape deviation and to the size of the relative position; n – the number of details surface areas in the product; $b_{\mathrm{PR}i}$ – the coefficient, taking into account the labor intensity of achieving precision A_i , when the part is processed, ranging from 0 to 1; $b_{\mathrm{PRS}i}$ – the area fraction of the i-th detail surface from the total surface area of all details in the product taken as a unit.

8. *Coefficient of details surfaces roughness:*

$$C_{\mathrm{RN}} = a_3 a_{32} \left(1 - \frac{n}{\sum B_i b_{\mathrm{RN}i} b_{\mathrm{SRN}i}} \right),$$

where B_i – the value of the i-th details surface roughness parameter in the product; $b_{\mathrm{RN}i}$ – the coefficient, taking into account the laboriousness of achieving the parameter B_i, when processing a detail, ranging from zero to one; $b_{\mathrm{SRN}i}$ – the area proportion of the i-th details surface from the total surface area of all details in the product taken as a unit.

9. *Coefficient of precision methods efficiency (for the closing links of dimensional chains)*:

$$C_{\mathrm{MDCH}} = a_3 a_{35} \left(\frac{\mathrm{CI} \cdot b_{\mathrm{P.CI}} + \mathrm{ICI} \cdot b_{\mathrm{P.ICI}} + \mathrm{GI} \cdot b_{\mathrm{P.GI}} + \mathrm{ADJ} \cdot b_{\mathrm{P.ADJ}} + \mathrm{FT} \cdot b_{\mathrm{P.FT}}}{n_{\mathrm{DCH}}} \right) +$$

$$+ a_3 a_{35} \left(\frac{\mathrm{CI} \cdot b_{\mathrm{M.CI}} + \mathrm{ICI} \cdot b_{\mathrm{M.ICI}} + \mathrm{GI} \cdot b_{\mathrm{M.GI}} + \mathrm{ADJ} \cdot b_{\mathrm{M.ADJ}} + \mathrm{FT} \cdot b_{\mathrm{M.FT}}}{n_{\mathrm{DCH}}} \right),$$

where CI – the number of dimensional chains, assembled by the complete interchangeability method; ICI – the number of dimensional chains, assembled by the incomplete interchangeability method; GI – the number of dimensional chains, assembled by the group interchangeability method; ADJ – the number of dimensional chains, assembled by the adjustment method; FT – the number of dimensional chains, assembled by the fitting method; $b_{\mathrm{P.CI}}$ – the coefficient of the influence degree of the complete interchangeability method on the production labor intensity; $b_{\mathrm{P.ICI}}$ – the coefficient of the influence degree of incomplete interchangeability method on the production labor intensity; $b_{\mathrm{P.GI}}$ – the coefficient of the influence degree of group interchangeability method on the production labor intensity; $b_{\mathrm{P.ADG}}$ – the coefficient of the influence degree of adjustment interchangeability method on the production labor intensity; $b_{\mathrm{P.FT}}$ – the coefficient of the influence degree of fitting method on the production labor intensity; $b_{\mathrm{M.CI}}$ – the coefficient of the influence degree of the complete interchangeability method on the manufacture labor intensity; $b_{\mathrm{M.ICI}}$ – the coefficient of the influence degree of incomplete interchangeability method on the manufacture labor intensity; $b_{\mathrm{M.GI}}$ – the coefficient of the influence degree of group interchangeability method on the manufacture labor intensity; $b_{\mathrm{M.ADG}}$ – the coefficient of the influence degree of

adjustment interchangeability method on the manufacture labor intensity; $b_{\text{M.FT}}$ – the coefficient of the influence degree of fitting method on the manufacture labor intensity.

10. *Connection coefficient:*

$$C_{\text{C}} = a_3 a_{35} \frac{\sum n_{\text{C}i} b_{\text{C}i} b_{\text{SC}i}}{n_{\text{C}}},$$

where $n_{\text{C}i}$ – the number of i-th type connections; n_{C} – the number of connections in the product; $b_{\text{C}i}$ – the influence degree of the i-th connection type on labor intensity (for cylindrical movable ones $b_{\text{C}i}$ will have a minimum value and for welded joints it will be maximum); $b_{\text{SC}i}$ – the contact areas proportion of the i-th connection type to total contact area of all joints in the product taken as a unit; a_{35} – the influence degree of L_{35} on L_3.

11. *Element mass coefficient:*

$$C_{\text{M}} = a_3 a_{33} \frac{\sum E_{\text{M}i} \cdot b_{\text{M}i}}{E_{\text{M}}} + a_3 a_{36} \frac{\sum E_{\text{M}i} \cdot b_{\text{M}i}}{E_{\text{M}}},$$

where $E_{\text{M}i}$ – the number of the i-th mass value elements; E_{M} – the number of PD elements; $b_{\text{M}i}$ – the influence degree of the i-th element mass value on manufacture labor intensity; a_{36} – the influence degree of L_{36} on L_3.

Coefficients a, reflecting the influence degree of manufacturability on labor intensity, are determined from the following relations:

$$a_2 = \frac{L_2}{L},\ a_{21} = \frac{L_{21}}{L_2},\ a_{22} = \frac{L_{22}}{L_2},\ a_{23} = \frac{L_{23}}{L_2},$$

$$a_3 = \frac{L_3}{L},\ a_{31} = \frac{L_{31}}{L_3},\ a_{32} = \frac{L_{32}}{L_3},\ a_{33} = \frac{L_{33}}{L_3},\ a_{34} = \frac{L_{34}}{L_3},\ a_{35} = \frac{L_{35}}{L_3},\ a_{36} = \frac{L_{36}}{L_3}.$$

The given calculation formulas of manufacturability coefficients make it possible to determine an integral assessment of the manufacturability level at the manufacturing stage by summing their values.

The manufacturability coefficients of disposal preparation and design production preparation are determined by the same method.

Specificity of the influence of the design labor intensity on the technological production preparation. In modern conditions of frequent production diversification and taking into account the specifics of some designs of mechanical engineering products, for example, cutting and measuring tools and means of technological and metrological equipment, the approach to determining the manufacturability coefficients should be somewhat refined for the design and technological production preparation. In particular, it is necessary to determine the frequency and duration of the use of tools and equipment in the production process.

For this, the details number and the frequency of structural elements, meeting the same type in terms of their characteristic standard size, for example, the diameter of the hole in the parts, are determined in the product [5, 17]. At the same time, in the process of design preparation for production, the structural elements sizes are estimated, which determine their production by cutting tools. Further, if necessary, in the process of technological production preparation, the duration of the use of auxiliary tools and equipment, machines and devices is taken into account.

Statistical data analysis can be represented by histograms of the frequency and duration of the encounter and the use of structural elements, cutting and measuring tools, etc.

Those constructive elements and, accordingly, tools that are rare, can be unified and replaced with frequently occurring ones.

The efficiency of using the cutting tool at the first level can be estimated by the coefficient of the conditional duration of use.

$$C_{\text{U}i} = \text{F}_i \cdot \text{D}_i,$$

where F_i and D_i – the frequency and duration of the detail element meeting and the use of the cutting tool, respectively.

Tools that are common and can be replaced by new, more effective ones, should be evaluated by the second level indicators. This compares the indicators of the basic (previously used) and new instruments.

The criteria can be used:

tool life coefficient:

$$C_{TL} = T_N/T_B,$$

where T_N and T_B – the durability periods of the new and basic tools, respectively;

machinability coefficient of detail material:

$$C_M = V_N/V_B,$$

where V_N and V_B – the cutting speeds with new and basic tools, respectively;

precision and quality coefficient:

$$C_{P,Q} = (IT, Ra)_B/(IT, Ra)_N,$$

where $(IT, Ra)_B$ and $(IT, Ra)_N$ – the precision and roughness of the machined surface of detail structural element with the basic and new cutting tool, respectively.

Indicators or criteria of the third level characterize the cutting tool at the manufacturing stage. In particular, the cost coefficient of the cutting tool is:

$$C_{CS} = C_B/C_N,$$

where C_B and C_N – the cost of the basic and new cutting tools, respectively;

payback coefficient of the cutting tool:

$$C_{PB} = CS_N/(C_B - C_N),$$

where CS_N – costs for a new cutting tool.

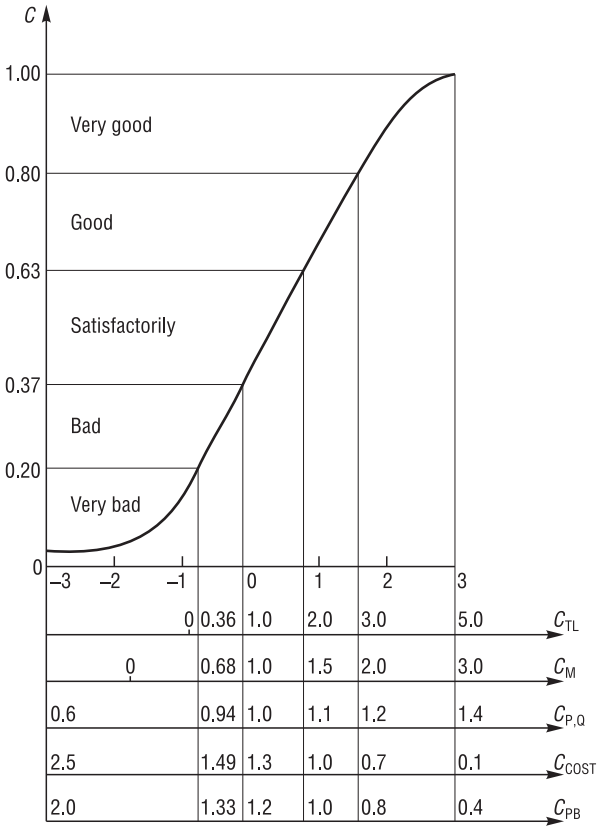

Figure. 2. Generalized desirability function of efficiency coefficient set of the tool use in production

The effectiveness of one or more candidate tools can be assessed at each of the given levels or in aggregate in points [5, 17]:

$$C_{EF} = C_U \cdot C_{TL} \cdot C_M \cdot C_{P,Q} \cdot C_{CS} \cdot C_{PB},$$

or by the generalized desirability function:

$$C_{DEF} = f(C_U, C_{TL}, C_M, C_{P,Q}, C_{CS}, C_{PB}).$$

The cutting tool with the highest C_{EF} score is considered the most effective.

Desirability refers to one or another level of a parameter or criterion for assessing the effectiveness of the cutting tool use. On a special scale, the desirability value can vary from 0 to 1 (Figure 2).

The values of $C_{DEF} = 1$ correspond to the maximum possible criterion level, and $C_{DEF} = 0$ – the minimum.

The desirability function is described by the expression:

$$C_{DEFi} = \exp(-\exp(C_i)),$$

where C_i – the dimensionless value of a parameter or criterion, given in accordance with the de-

sirability scale [16, 18]. The generalized desirability function is formed as the geometric mean of the desirability parameters:

$$C_{\text{DEF}} = \sqrt[n]{C_{\text{DEF}_1} \cdot C_{\text{DEF}_2} \cdot \ldots \cdot C_{\text{DEF}_n}}.$$

As a result, to determine the effectiveness of the tool use, an expert system has been proposed, which includes: a database on certain parameters of products, parts, cutting and measuring tools and other objects of the technological environment; analysis methods, using mathematical statistics of the frequency and duration of the detail elements, tools and other objects meeting; procedures for assessing the condition of the instrument at the stages of its manufacture, operation and disposal.

Conclusion. On the technical and economic analysis basis of the relation properties between design and technological solutions, a method for the integral assessment of production manufacturability in the life cycle of a product is proposed.

The assessment method combines various manufacturability coefficients, taking into account their influence degree on the labor intensity of production and maintenance, repair and disposal of the product structure.

An effectiveness examination of the tool, equipment and other objects use of the technological environment at the stages of design and technological production preparation has been formalized.

Based on the results of the technical and economic assessment, it is proposed to understand the product design manufacturability at the stages of its production and disposal as production manufacturability.

References

1. Kheifetz M. L. (ed.) *Quality Assurance of Products in Technological Complexes*. Minsk, Belaruskaya navuka Publ., 2019. 248 p. (in Russian).

2. Vasiliev A. S., Dal'sky A. M., Klimenko S. A., Polonski L. G., Kheifetz M. L., Yashcheritsyn P. I. *Technological Bases of Machine Quality Management*. Moscow, Mashinostroenie Publ., 2003. 256 p. (in Russian).

3. Dal'sky A. M., Bazrov B. M., Vasiliev A. S., Dmitriev A. M., Kolesnikov A. G., Kondakov A. I., Shachnev Ya. A. *Technological Strain in Mechanical Engineering*. Moscow, Moscow Aviation Institute, 2000. 364 p. (in Russian).

4. Kheifetz M. L., Chemisov B. P. (eds.) *Intellectual Production: State and Prospects*. Novopolotsk, Polotsk State University, 2002. 268 p. (in Russian).

5. Kheifetz M. L., Tochilo V. S., Semenov V. I., Kukhta S. V., Kosyak L. N. *Statistical Analysis of Structural Elements and Technological Parameters of Machine Parts*. Novopolotsk, Polotsk State University, 2001. 112 p. (in Russian).

6. Korshunov Yu. M. *Mathematical Foundations of Cybernetics*. Moscow, Energoatomizdat Publ., 1987. 496 p. (in Russian).

7. Ebeling W. *Strukturbildung bei Irreversiblen Prozessen* [Formation of Structures in Irreversible Processes]. Leipzig, Teubner-Verlag, 1976 (in German).

8. Sigorskii V. P. *Engineer's Mathematical Apparatus*. Kiev, Tekhnika Publ., 1977. 768 p. (in Russian).

9. Haken G. *Synergetics*. Wiesbaden, Vieweg+Teubner Verlag, 1973. https://doi.org/10.1007/978-3-663-01511-6

10. Bazrov B. M., Kheifets M. L., Popok N. N. Unification of Design Decisions on the Basis of Average Distribution of Probabilities and Introduction of Isolated Areas for Elements of Products Described by Structured Multiple Modules. *Nonlinear Phenomena in Complex Systems*. 2019, vol. 22, no. 3, pp. 221–232. https://doi.org/10.33581/1561-4085-2019-22-3-221-232

11. Gordienko A. I., Kheifetz M. L., Kozhouro L. M., Rakomsin A. P., Sidorenko M. I., Eidelman E. D., Senchilo I. A. *Combined Physico-Chemical Treatment: Synergetic Aspect*. Minsk, Technoprint Publ., 2004. 200 p.

12. Amirov Yu. D., Alferova T. K., Volkov P. N. *Manufacturability of Product Designs*. Moscow, Mashinostroenie Publ., 1985. 368 p. (in Russian).

13. Balabanov A. N. *Manufacturability of Structures of Machine Parts*. Moscow, Mashinostroenie Publ., 1987. 336 p. (in Russian).

14. Bochkarev P. Yu., Bokova L. G. *Assessment of Production Manufacturability of Parts*. Moscow, Lan' Publ., 2017. 132 p. (in Russian).

15. Bazrov B. M., Troitskii A. A. Analysis of the coefficients of manufacturability of the design of the product. *Naukoemkie tekhnologii v mashinostroenii = Science Intensive Technologies in Mechanical Engineering*, 2018, no. 7, pp. 23–26 (in Russian).

16. Troitskii A. A. Calculation formulas for the coefficients of production manufacturability of product design. *Naukoemkietekhnologii v mashinostroenii = Science Intensive Technologies in Mechanical Engineering*, 2020, no. 8, pp. 25–28 (in Russian).

17. Popok N. N. *Mobile Reorganization of Engineering Production*. Minsk, Technoprint Publ., 2001. 396 p. (in Russian).

18. Kheifetz M. L. *Mathematical Modeling of Technological Processes*. Novopolotsk, Polotsk State University, 1999. 104 p. (in Russian).

Information about the authors

Boris M. Bazrov – D. Sc. (Engineering), Professor, Head of the Laboratory, Mechanical Engineering Research Institute of the Russian Academy of Sciences (4, Maly Kharitonyevsky Pereulok, Moscow, 101990, Russian Federation). E-mail: modul_lab@mail.ru

Mikhail L. Kheifetz – D. Sc. (Engineering), Professor, Director, Institute of Applied Physics of National Academy of Sciences of Belarus (16, Akademicheskaya Str., Minsk, 220072, Republic of Belarus). https://orcid.org/0000-0002-6942-3605. E-mail: mlk-z@mail.ru

Valery L. Hurevich – Ph. D. (Engineering), Associate Professor, Director, Belarussian State Institute of Metrology (16, Starovilenskiy Tract, Minsk, 220072, Republic of Belarus). E-mail: hurevich@belgim.by

Nikolay N. Popok – D. Sc. (Engineering), Professor, Head of the Department, Polotsk State University (29, Blokhin Str., Novopolotsk, 211440, Republic of Belarus). E-mail: n.popok@psu.by

Информация об авторах

Базров Борис Мухтарбекович – доктор технических наук, профессор, заведующий лабораторией, Институт машиноведения имени А. А. Благонравова Российской академии наук (Малый Харитоньевский пер., 4, 101990, Москва, Российская Федерация). E-mail: modul_lab@mail.ru

Хейфец Михаил Львович – доктор технических наук, профессор, директор, Институт прикладной физики Национальной академии наук Беларуси (ул. Академическая, 16, 220072, Минск, Республика Беларусь). https://orcid.org/0000-0002-6942-3605. E-mail: mlk-z@mail.ru

Гуревич Валерий Львович – кандидат технических наук, доцент, директор, Белорусский государственный институт метрологии (Старовиленский тракт, 16, 220072, Минск, Республика Беларусь). E-mail: hurevich@belgim.by

Попок Николай Николаевич – доктор технических наук, профессор, заведующий кафедрой, Полоцкий государственный университет (ул. Блохина, 29, 211440, Новополоцк, Витебская обл., Республика Беларусь). E-mail: n.popok@psu.by