UDC 621.001.2
DOI: 10.15587/2312-8372.2018.129676

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SUBSTATIATION OF QUANTITATIVE CRITERIA OF STRUCTURAL PARTS AND UNITS MANUFACTURABILITY EVALUATION

Об'єктом дослідження є складаність та ремонтопридатність конструкцій. Критерії оцінки таких важливих параметрів технологічності конструкції є надзвичайно складною проблемою процесу конструювання. Як відомо, результатом конструювання має стати втілення ідеї в формі виробу. Низька технологічність суттєво ускладнює даний процес, або взагалі унеможливлює.

Одним з найбільш проблемних місць при визначенні критеріїв складаності та ремонтопридатності конструкцій є те, що їх перелік відрізняється залежно від конструкції. Із збільшенням числа деталей в конструкції процес визначення критеріїв та їх кількісна оцінка значно ускладнюються.

Формалізація критеріїв технологічності дозволяє звести процес оптимізації до єдиного алгоритму, який має високу ступінь автоматизації. Потенціал реалізації теорії в системах автоматизованого проектування став відправним пунктом для проведення дослідження.

Використання результатів дослідження, а саме сформульованих теорем складаності та ремонтопридатності, дозволяє оптимізувати конструкцію і оцінити результати оптимізації якісно та кількісно. Найдоцільніше застосовувати зазначені результати для конструкцій, виробництво яких передбачає серійність – масове та крупносерійне виробництво. За таких умов економічний ефект від запровадженої оптимізації найбільш відчутний.

Ще однією перевагою дослідження є відповідь на запитання – за якого найбільшого числа найменувань елементів конструкції можливе досягнення максимальної складаності та ремонтопридатності? Сформульовані висновки вносять зміну в алгоритм проектування конструкції і програмують рівень її оптимальності вже під час проектування. Саме такий підхід зменшує рівень матеріальних витрат вже на етапах проектування, технологічної підготовки виробництва, і, безпосередньо, під час виробництва.

Фактичним результатом застосування розробленої методики оптимізації є підвищення технологічності досліджуваних конструкцій від 30 до 50 %. В порівнянні з відомими аналогами, створено підґрунтя для встановлення та комплексного аналізу критеріїв технологічності як результату взаємодії складаності і ремонтопридатності.

Ключові слова: *рівень технологічності конструкцій, критерії оцінки складаності, критерії оцінки ремонтопридатності.*

1. Introduction

The achievement of high technological design remains an urgent task with a reduction in the cost of products, increasing their maintainability. Manufacturability is due to the methods of construction – geometric, machine-building, basic, etc. – however, the perfection of the structure is of primary importance for manufacturability. Rationality of the structure of products is reflected in certain regularities, which it is advisable to know the designers and technologists. Particularly useful for a priori evaluation of designs may be quantitative criteria that take into account these patterns. The solution of this scientific problem is facilitated by the creation of a theory that will unite and reveal the essence of many positive but multifaceted results obtained in the design. Based on the experience of the development of other sciences, this theory should be axiomatic. In our time there is no formalized theory of the structure of machines and devices with quantitative criteria for assessing the manufacturability of their parts and assemblies. This hinders the use of CAD systems, since only those CAD systems which «objects of research» have a serious formalized theoretical basis with a developed mathematical-logical apparatus are «effective». At the heart of such base should be a systematic approach.

2. The object of research and its technological audit

The object of research is the assemblability and maintainability of structures and the criteria for their evaluation.

In assemblability products, we also have in mind the manufacturability of assembly, and under maintainability – the technological nature of the repair. Both these concepts are connected by certain dependencies with the quantitative composition of products. In the aggregate assemblability and maintainability determine the manufacturability.

For operating objects of research, they must be given certain qualitative and quantitative signs, which are the basis for analysis, improvement and comparison. As such signs, let's accept quantitative criteria of assemblability and maintainability.

The quantitative criterion for the assemblability of mechanisms is defined as the ratio of the number of possible subsets of the different joining sequences of parts and assemblies to the number of corresponding assembly units.

The quantitative criterion of maintainability is formulated as the ratio of the set of parts and assemblies that can be removed without removing other parts and assemblies to the total number of details of this assembly unit.

The main problematic place of the investigated criteria is that they depend on each specific design to which they should be applied. It is impossible to create a universal list of criteria for manufacturability. In addition to the above, it is important to understand that with the increase in the structural units of the design, the initial assessment of its manufacturability is significantly more complicated. However, the fuzzy list of qualitative and quantitative criteria has no influence on the algorithm for their analysis and optimization. Thus, the study is devoted to the formalization of the process of improving structures in the direction of increasing manufacturability by certain criteria.

3. The aim and objectives of research

The aim of research is the creation of a priori quantitative criteria of manufacturability of assembly, repair and unification of structures, according to which it is possible to evaluate the conformity of the structure of structures to the given technical and technological levels. This will allow to identify the patterns and determine the ways to optimize the structures even at the design stage, coordinating them with the technological equipment, as well as introducing the proven concepts of estimating constructions with quantitative criteria into standards.

To achieve this aim, it is necessary to solve the following tasks:

1. To substantiate the creation of a priori quantitative criteria for assemblability and maintainability on the basis of the mathematical concept of «set of subsets» by proving the theorem on maximum assemblability and maintainability of constructions by induction.
2. To create quantitative criteria for unification, based on the concept of the primary element, and justify them by proving the theorem on maximum unification.
3. According to the received criteria, to work out the designs for manufacturability in accordance with the requirements of production.

4. Research of existing solutions of the problem

At present, quantitative indicators of the manufacturability evaluation of assembly and repair of mechanisms and devices are determined on the basis of the basic equations of labor intensity and cost [1–5]. These indicators are dependent on the state of the technology of a particular enterprise, the qualifications of its personnel and other, time-varying factors [5]. With this approach, the indicators of manufacturability are characterized not so much by technological design as by the level of technology and organization of production of a particular enterprise that specializes in assembly or repair [5, 6]. These indicators depend on the type of production (single, serial, large-scale, mass), and from other factors, which, in sum, distort the overall evaluation of manufacturability, especially for the first time mastered products [7]. These indicators, due to their specificity, do not allow quantifying the manufacturability of products at the stage of their development [5–8]. As a result, many shortcomings associated with the technological design of the structures are delayed, when the equipment of the first stage has already been manufactured and the production at the enterprise is being carried out [9]. Inevitably, the processing of structures results in significant inadvisable production costs [8].

It is necessary to observe and qualitative criteria, such as the convenience of access to various places of the product, the possibility of using a standard tool for repairs, etc. [10]. However, the lack of a priori quantitative criteria for assessing the manufacturability of assembly and repair and, consequently, of the corresponding structures, hinders the increase in economic indicators of production and operation of products [11, 12].

The systematization of research results shows that the quantitative criterion should be put in the basis of assembly and repair manufacturability, it will be possible to objectively evaluate and initiate the improvement of the manufacturability of structures already at the initial stages of their creation [11–13]. This problem can be solved by establishing the composition of a priori quantitative criteria, deducing theorems, and then creating corresponding laws.

5. Methods of research

The following theories and scientific methods are used in the study:

- set theory in the search for regularities in the structure of machine and instrument constructions and group theory in determining first-order predicates;
- method of classification, finite element method and formalized method of analysis, synthesis and optimization of structures when creating a priori quantitative criteria of assemblability, maintainability and unification;
- axiomatic method, as one of the methods of deductive construction of scientific theories while ensuring the rigor of these theories;
- method of induction in the proof of the theorem on maximal assemblability and maintainability. This method is used as a logical method of research, which allows to generalize the research results by the movement of thought from the individual to the general;
- method of apagogical proof in the proof of the theorem on maximum unification;
- method of generalizing and optimizing results in the derivation of the law on assemblability and maintainability and the law on the unification of parts;
- system-structural method in the analysis of structural details according to the formulated criteria of assemblability, maintainability and unification.

6. Research results

6.1. Creation and substantiation of quantitative criteria of the theorem on maximum assemblability and maintainability of structures. In the work under the assemblability of products, let's have in mind the manufacturability of the assembly, and under the maintainability – the repair manufacturability. Both these concepts will come out of the quantitative composition of products.

The research carried out by the authors shows that the a priori quantitative criteria of assemblability and maintainability can be created on the basis of the mathematical concept of «set of subsets (set-degree)» [14–16].

A set-power is a set, which elements are all subsets of any fixed set [15–18]. For example, for three-element sets $A=\{a, b, c\}$ [17]:

$$P(A)=\{\varnothing,\{a\},\{b\},\{c\},\{a,b\},\{a,c\},\{b,c\},\{a,b,c\}\}, \quad (1)$$

where $P(A)$ – set-power of the set A; $\varnothing$ – empty set; a, b, c – elements of the set A.

So, the design has the maximum assemblability and maintainability, if it is possible to assemble/disassemble in any sequence and provides the possibility of installing/removing each part or assembly without installing/removing another part or assembly. That is, the design defines the order of the location of parts and assemblies, and the sequence of assembly or disassembly can be arbitrary at each structural level of the specified product composition.

The quantitative criterion for the assemblability of mechanisms and devices (assembly units) is defined as the ratio of the power of the set of possible (real) subsets of different sequences of joining parts and assemblies to the power of multiple degrees of these assembly units:

$$K^c=\frac{m(P)^c+1}{m(P_n)}, \quad (2)$$

where K^c – assembly criterion; $m(P)^c$ – the cardinality of the set of real subsets of the assembly unit that can be obtained by addition (the unit is added to allow for the empty set that enters the denominator); $m(P_n)$ – the power of the multiple power of the assembly unit, which is determined solely on the basis of its composition.

The possible (real) subsets of the assembly are those subsets whose formation allows the assembly process. In determining subsets, as a rule, only the names of parts and assemblies of a particular assembly unit are taken into account. The structural levels in the construction are treated similarly to [16, 17].

Quantitatively the criterion of maintainability of the assembly unit is logical to define as the ratio of the power of a set of parts and components that can be removed without removing other parts and assemblies to the power of multiple degrees of this assembly unit:

$$K^P=\frac{m(P)^P+1}{m(P_n)}, \quad (3)$$

where K^P – repairability criterion; $m(P)^P$ – power of the set of real subsets that can be obtained with any sequence of disassembly of the assembly unit at a certain level, taking into account it itself (the unit in the numerator is added, given the presence of an empty set in the denominator); $m(P_n)$ – power of the plural-degree of the assembly unit, which is calculated, based, as a rule, only on the number of items of parts and nodes at this level of disassembly.

Theorem on maximum folding and repairability of structures. In order to substantiate the quantitative criteria let's prove the following theorem: the assembly unit has the maximum folding and repairability, if the construction of its structure provides a real possibility of obtaining at all the corresponding structural levels of all subsets in a similar way to the set-degree. Formalized entry of the theorem:

$$\forall K((((m(P)^c+1)=(m(P)^P+1)= \\ =m(P_n))\wedge K^c\wedge K^P)\Rightarrow(\max K^c\wedge\max K^P)), \quad (4)$$

where K – any assembly unit.

Let's carry out the proof by induction [18–22]. Take the structure of the assembly, consisting, for example, of the base, sheet metal part and fastening. It can be fastening the skin to the body of the gas generator (Fig. 1). Let's define the power of the multiple power of this assembly unit:

$$m(P_n)=2^n,$$

where $m(P_4)=2^4=16$.

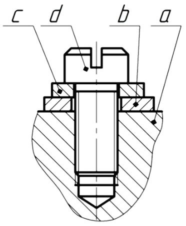


Fig. 1. Schematic drawings of a simple assembly unit with $K^c=K^P=0.5$: *a* – gas generator body; *b* – thermal sheathing; *c* – washer; *d* – screw

The actual number of subsets in the assembly (disassembly) will be as follows:

$$P_{(a,b,c,d)}=\{a\},\{d\},\{a,d\},\{b,c\},\{c,d\},\{b,c,d\},\{a,b,c,d\}\}. \quad (5)$$

That is, $m(P_{(a,b,c,d)})=7$, since it is impossible to get more subsets without constructive changes during assembly and disassembly. Let's define the quantitative criterion of assemblability and maintainability of the considered unit:

$$K^c=K^P=\frac{m(P_{(a,b,c,d)})+1}{m(P_4)}=0.5.$$

Consequently, this assembly unit has a low assemblability and maintainability. If the washer is not installed, then $K^c\cdot K^P=0.75$. The criterion value has grown, but has not reached the maximum possible. The maximum (one) criterion of assemblability and maintainability will be when the node consists of two elements (Fig. 2), or of three elements, provided that the screw head and the hole under it have a special shape (Fig. 3).

Details *b*, *c*, *d* (Fig. 2) are combined into a separate node and make up one element. The gas generator body *a* is the second element of this assembly unit. In this variant, the manufacturing of the screw *d* is somewhat more complicated. In addition, in the sheating *b*, the screw hole *d* must be threaded, although it may be incomplete because it is not fastening.

This feature can be eliminated if the thread on the screw *d* is obtained by knurling (the diameter of the screw shaft *d* in the places free from knurling will be smaller than the outer diameter of the thread). The hole for screw *d* in the sheating *b* should be made with a small flange, which is crushed when the screw *d* is first screwed and, further, prevents the screw from falling out of the hole (Fig. 4).

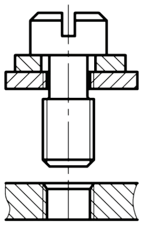
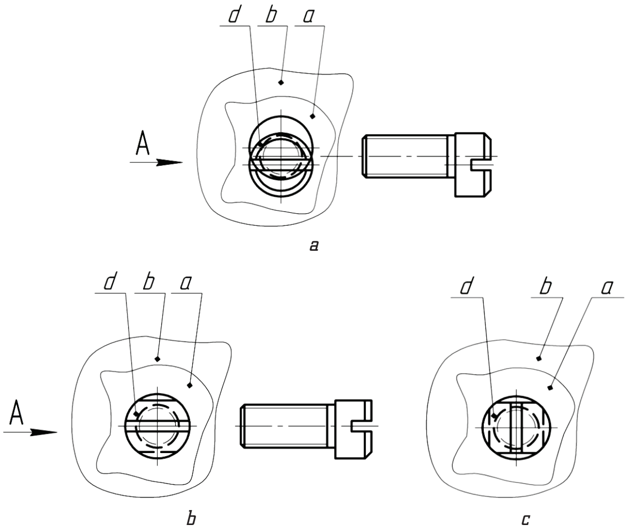


Fig. 2. The assembly unit obtained by the transformation of the construction in Fig. 1

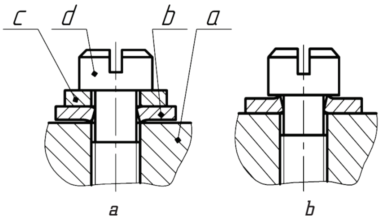


a

b

c

Fig. 3. Variants of the mounting assembly $K^c = K^P = 1$, where *a* – the body of the gas generator; *b* – thermal sheathing; *d* – screw: *a* – option 1; *b* – option 2; *c* – option 3



a

b

Fig. 4. Variants of transformations of the assembly unit shown in Fig. 2: *a* – gas generator body; *b* – thermal sheathing; *c* – washer; *d* – screw. $K^c = K^P = 1$: *a* – option 1 with a washer; *b* – option 2 without washer

Also, the issue is solved using self-tapping screws. The shapes of the heads and, correspondingly, of the holes for them, can be varied and not exhausted, as shown in Fig. 3, 4. This indicates the ability to meet the various requirements for the assembly unit.

When calculating quantitative criteria, the number of elements in the assembly unit is taken into account only for the structural level in question, with the same elements being taken as one element [21, 23, 24]. For example, the sheating b is fastened with four screws, but in subsets the screw will be considered a name, without taking into account the number of these screws in a specific assembly unit, at a specific structural level. In this case, this applies to the washers, and in general – all the repeated parts and assemblies. However, if an element is applied in a node at the same structural level, but also for a different purpose, or as part of other elements, then these applications are counted as additional elements in those subsets to which they belong.

So, there is a tendency when, with a reduction in the number of parts or assemblies combined into an assembly unit, the level of assemblability and maintainability increases. The above examples can be considered as an inductive confirmation [19] of the possibility of reducing the number of elements or their rearrangement by nodes in any assembly unit without reducing its parameters. The inductive proof of the theorem is considered complete.

Corollary I. Assemblability and repairability of the assembly unit increase with decreasing its quantitative composition.

The formalized notation of Corollary I:

$$\forall K(((K^c \wedge K^P)\rightarrow \max)\Rightarrow(m\rightarrow \min)), \qquad (6)$$

where m – the number of names of parts and/or assemblies in the assembly unit at the considered structural level.

Corollary I is actually present in the proof of the theorem. In addition, one should take into account: the set-power $m(P^n)$ is equal to 2^n, where n is the number of elements of the initial set; so if add only one element, then the number of variants of the assembly (disassembly) will be doubled: 2^{n+1}. For example, for $n=3$, $m(P_3)=8$, for $n=4$, $m(P_4)=16$, etc. That is, the number of options for assembly (disassembly), for which the design needs to create the possibility of implementation, increases dramatically and it is practically impossible to implement them. In this case, the number of elements of a multiple degree is understood to be the number of subsets, subject to the law of idempotency [17]. In other words, only the number of names of parts (nodes) in the assembly unit is considered, and at a specific structural level of assembly (disassembly). Instead of the term «part/assembly name», the term «size» is used in the work for parts and components that are functionally allocated and close to their intended use.

Corollary II. There is an important question in the design of machines and devices – in which the largest number of items in the assembly unit is reliable to achieve maximum assemblability and maintainability?

Fig. 4 shows the ternary design, which has the maximum assemblability and maintainability. The insertion of the washer under the screw head will degrade this parameter by half. In the washer, the shape of the hole can be made to the corresponding screw head and thus improve this figure. However, this is unacceptable, since the processes of assembly and disassembly are complicated. If the changes are made (Fig. 3, *a, b*), then at the given structural level two elements are formed, of course it will make the parameter maximum, but the question for the collapsible design with a large number of elements will not solve the problem. Consequently, with four elements to achieve maximum assemblability and maintainability is impossible, with three – it is possible.

Let's consider any more complex construction, for example, gas generator chamber for gasification of solid fuel [25]. The gas generator consists of a bunker connected to a mine, in the lower part of which there is a gas-forming chamber with windows in which blowing tuyeres are installed. It has a variator, which consists of a drive kinematically connected to the stirrer by devices made in the form of pneumatic cylinders. The front covers of the casing of the pneumatic cylinders are connected to blowing lances. The rods are installed with the possibility of reciprocating along the axes of the tuyeres. The tuyeres are made in the form of ball supports and are installed in the windows along the perimeter of the chamber in at least two tiers [25].

The construction [25] has insufficient assemblability and maintainability. Fastenings of pneumatic cylinders, ensuring the operability of the structure at high temperatures are complicated. It is technically difficult to arrange the stirrer's arrangement inside the tuyeres and to ensure its trouble-free operation due to the ingress of particles of fuel or ash into the space between the stirrer and the tuyere. According to the author [25], it is difficult to realize the possibility of free movement of the stirrer and each tuyere separately in order to form a combustion zone in practice. The design does not provide for the performed monitoring of the state of the fuel layers in the gas formation chamber at a certain time, and the chaotic movement of the tuyeres in the respective zones has a negative effect on the stability of the gassing process. The manufacture of such camera is a laborious process, and continuous work to restore the nodes of this camera through frequent failures increases the operating cost of the gas generator as a whole.

In order to simplify the assembly process and increase the maintainability, the design of the chamber for gas formation is proposed [26]. The oxidizing mixture enters the pyrolysis zone from the blast gas supply system through an air distributor, a flexible hose system and tuyeres installed in hinged supports. Supports are located in one or more tiers along the perimeter of the chamber. Movement of tuyeres is carried out by a system of levers, the position of which is changed by means of control discs. Compensation for the change in the length of the lever, which occurs during the movement, occurs due to the mobile connection presented in [26].

In the construction [26], the cylinders are replaced by a system of levers, driven by control discs. This gives significant savings, as cost-based operations for adjusting and stabilizing the system are eliminated. In this case, the determination of the quantitative composition takes into account the peculiarities of the blast gas supply system with the mandatory presence of tuyeres for the gasification process.

For inductive proof of the implication of the corollary II, the constructions considered are completely sufficient. Any assembly unit, if necessary, it is possible to make a ternary and achieve maximum assemblability and maintainability. In the group theory [27], the associativity of the composition law is noted for only three elements. So, the corollary II can be represented as: the ternary composition of the assembly unit is the largest for obtaining maximum assemblability and maintainability.

The formalized record of the corollary II:

$$\forall K((m \le 3) \Rightarrow ((K^c \wedge K^P) = \max)). \tag{7}$$

6.2. The law of assemblability and maintainability. From the point of view of formal logical constructions, formula (4) is identically true, as evidenced by its scheme $(A \wedge B \wedge C) \Rightarrow (B \wedge C)$, where A replaces the expression $((m(P)^c+1) = (m(P)^P+1) = m(P_n)$ and B is K^c, $C - K^P$.

Semantically, the truth of the quantitative criteria in formula (4) is their maximum value. These criteria are level. In the formula, they are connected by conjunctions, and therefore the right-hand side of formula (4) will be true in a meaningful sense with a large value of both criteria. Formally, for the truth of the implication, the truth is only the consequent. Thus, formula (4) is also meaningful. These properties of this formula indicate its general significance, which gives reason to consider it a law. Corollaries I and II further strengthen this assertion, and they are also rules of construction.

The law of assemblability and maintainability of structures can be formulated as follows:

The maximum assemblability and maintainability by structure is achieved in each design, if in the presence of a given order of location of the parts it is possible to have an arbitrary sequence of assembly (disassembly) of the corresponding assembly unit at a given structural level.

The illustration of the law is an example in the proof of a theorem and corollaries. The number of examples can be increased. In this case, known devices often need to be re-designed, and in many cases let's obtain designs containing novelty and utility, that is, they refer to inventions.

The law of assemblability and maintainability, not being a method of creating inventions, still initiates the development of new technology, as it prompts the search for fundamental changes aimed at improving the technological design of structures. After all, often the cause of poor performance mechanisms and devices is the lack of manufacturability [28, 29].

6.3. Creation and justification of quantitative criteria for unification. Current normative and technical documents and published works on unification consider and establish requirements, basically, to unification of assembly units [1, 30, 31]. Methods for the unification of parts have not been developed sufficiently.

In [3] it is stated that the unification of the parts must come from their elements, but the methods for carrying it out are not disclosed. The lack of a comprehensively grounded approach to the unification of parts reduces the effectiveness of unification and assembly units.

The modern design and technological concept tends mainly to static forms of unification, which, obsolete, can have a negative impact on the development of technology. The introduction of dynamic unification, organically including the evolution of its forms depending on the degree of progress of technology, is constrained by the lack of methods, first of all, the unification of parts.

The quantitative criterion for the unification of parts should be based on the concept of the primary element, as a simple part having a low structural level [8]. In addition, the emphasis in unification on the simplest parts makes it possible to assert a priori the construction of an elementary unification theory. The correctness of this approach is confirmed by the experience of creating mathematical theories, often started as elementary (elementary arithmetic, number theory, etc.).

First let's prove the theorem on maximal unification. The unification operation in this case is presented in the set-theoretic sense [15].

Definition of the theorem – if the elementwise elemental combining is equal to one primary element and then unification of these details will be maximum.

A formalized statement of the theorem:

$$\forall d\left(\left(\left(d \in D \in U\right) \wedge \left(\bigcup_{a_0} D = a_0\right) \wedge K^Y\right) \Rightarrow \left(K^Y = \max\right)\right), \quad (8)$$

where d – detail of a given type; D – specified type of parts, which is considered at the level of their elements; U – basic set; a_0 – primary element; K^Y – quantitative unification criterion.

Let's apply the proof by contradiction, that is, an indirect (apagogical) proof. Let's suppose that the negation of the theorem is true. However, in engineering, there are many examples of component designs, each of which is a primary element, repeated a finite number of times, namely:

- cylindrical helical springs (without pressurized and machined turns);
- parts made by cross-cutting of rolled products (channels, pipes);
- parts from plastics, formed from extruded blanks, etc.

The primary elements are: in the cylindrical springs – one turn, for the parts from the rolling – the section of the minimum length, etc. In such cases, the unification will be the maximum, since it is possible to obtain any size of the part. Thus, let's arrive at a contradiction about the negation of the theorem and, therefore, assert its truth.

Let's single out one more point, which, in fact, is a consequence of the above theorem: completely original there is a detail in which the intersection with the details of one or several are taken into account, the types is zero. Here, also, the operation of intersection is presented in the set-theoretical sense [15].

The above results actually imply the following construction of a quantitative criterion for the unification of details:

$$K^Y = \frac{1}{n_a}, \quad (9)$$

where n_a – the number of primary kinds of elements in the element-by-element association of the considered parts. For example, for one primary element, the unification will be maximal, since $n_a = 1$ and $K^Y = 1$. For two primary elements $n_a = 2$ and $K^Y = 0.5$, that is, the unification has deteriorated, and so on.

The law of unification of details. The necessity of a correct construction of the theory leads to a verification of the results obtained for the presence of regularity. The theorem on maximum unification and implication from it is a consequence and criterion is logically understandable. The syntax of formula (8), its scheme, causes the identical truth. Semantically, formula (8) is always satisfied, as evidenced by the substitution in it of objective data on various constructions, that is, this formula is true in each structure. Therefore, there is reason to assert that the results described by the models are of general significance for the unification process, they interpret formula (8). Thus, it is expedient to give the received results the form of the law on unification of details. The definition of the law – the unification of the detail increases with a decrease in the number of types of primary elements of its components and becomes maximum in one form.

Achieving the maximum value of the unification criterion for many types of parts is a complex and time-consuming task. Therefore, in the applied aspect, for such types it is appropriate to talk about the tendency to reduce the number of types of primary elements in detail, and will serve to increase unification.

The development of elemental unification is one of the components of its dynamic form. In particular, in the new unified parts, the «old» unified elements should be optimally used. Arguing abstractly, it can be argued that when minimizing the size of primary elements, at which limit levels an element is formed, from which by multiple repetitions it is possible to construct any complex detail that is very far from the current concept of a unified detail. Taking this into account, further research is planned to devote to the requirements that the primary element must satisfy from the standpoint of manufacturability, functioning, etc.

7. SWOT analysis of research results

Strengths. The strengths of this research are the formalization of the concepts of assemblability and maintainability and the associated process of establishing the necessary and sufficient number of relevant criteria. Special mention should be made of the universality of research results embodied in the relevant laws. The effect of the formulated laws of assemblability and maintainability covers not only the field of engineering for structures of any complexity, but can extend to any multicomponent systems.

As a consequence, the use of the design optimization method proposed in the study is the creation of such machine designs, the optimality of which in terms of assemblability and maintainability is laid at the design stage. In addition to direct advantages in the operation of optimized mechanisms and devices, they have increased manufacturability in their production. This affects the life cycle of the design, shortening the manufacturing stage and, accordingly, reducing its cost price.

Weaknesses. The weaknesses lie in the complexity of automating the process of identifying and analyzing the main criteria of assemblability and maintainability. Unfortunately, this process requires the involvement of experts, that is, the intervention of human intelligence and is currently not sufficiently algorithmized for use in CAD. On the other hand, other optimization steps can be automated by using the research results, of course, if there are expert evaluation results of the relevant criteria. In addition, the proposed theory limits the number of criteria necessary for optimization, which greatly simplifies the work of experts and shortens the time for their evaluation. Acceleration of the design process will speed up its manufacturing and, accordingly, increase its competitiveness through temporary advantages in entering the outlets.

The constant development of technologies requires the constant creation of new designs of mechanisms and devices, and the requirements for their storage and maintainability are increasing. For example, assemblability today is increasingly determined by the ability to conduct automated, mechanized and robotic operations. The same goes for repairs, work on the automation of processes which are constantly being conducted.

Opportunities. Opportunities for further research in this case should be focused on the possibility of applying the formulated laws for the design of manufactured and repaired structures in the conditions of modern and future automated and robotic industries.

Potential profitability of the introduction of such technology is illustrated, first of all, by the time spent on assembly. So, the duration of the assembly cycle of the design, created on the basis of the proposed methods and laws, is significantly reduced in comparison with the constructions created without taking into account the optimization criteria. Reduction of the assembly time can reach 30–50 %.

Threats. The main «threat» to the introduction of research results in life is the need to involve a group of experts whose qualifications in designing designs for this assignment should be as high as possible. Unfortunately, in the absence of a common database of specialists in the field of machine building, it is rather difficult to quickly find an expert group. In addition, the involvement of experts is associated with additional costs, the magnitude of which increases significantly with increasing requirements for their qualification. Ways to overcome this threat are associated with further research and the creation of a number of algorithms for the automated evaluation of quantitative criteria for typical structures and structures derived from them.

8. Conclusions

1. A priori quantitative criteria of assemblability and maintainability based on the mathematical concept of «set of subsets» are created. These criteria allow quantifying the manufacturability of products at the stage of their design and do not depend on changes in time factors such as the technology of a particular enterprise, the qualifications of personnel, etc. To substantiate the quantitative criteria, the theorem on the maximum storage and maintainability of structures from consequences of I and II with induction is proved. The high importance of the theorem makes it possible to consider it a law. Corollaries I and II, being the rules of construction, further strengthen this assertion. A distinctive feature of the law is that, as a method of creating inventions, it initiates the development of new technology, since it leads to search for fundamental changes aimed at improving the technological design of structures in order to obtain a priori criteria.

2. The methods for the unification of parts are disclosed. Quantitative criteria for the unification of parts, based on the concept of the primary element, have the lowest structural level. An apagogical proof of the theorem on maximal unification is proposed. It is established that there is a completely original detail in which the element-by-element intersection with details of one or several types is taken into account is equal to zero. The theorem is checked and the consequences implied by it for the existence of a regularity. The syntax of the obtained formula and its scheme determine the identical truth, semantically it is always fulfilled, as evidenced by the obtained practical results. The general significance of the obtained results for the process of unification of parts allows them to be embodied in the form of a law on the unification of parts.

3. The obtained results allow to state that when minimizing the sizes of primary elements at what limit levels an element is formed from which by means of repeated repetitions it is possible to construct any complex part corresponding to the requirements set forth in terms of technology and functioning:

- nomenclature of aggregate installation of mechanisms and devices;
- introduction of systems of modular design taking into account typification and unification;
- use of CAD, which provide a given level of analysis of options for design solutions for various schemes of their use.

The practical value of the obtained results consists in the possibility of creating on the basis of quantitative criteria an automated system of expert selection of an optimal basic design with the maximum potential for functional improvements, with the subsequent definition of a complex measure of manufacturability. This system can be part of a general production system that will provide the ability to manage quality and can be built into integrated CAM/CAD systems. The use of this system will ensure a reduction in the labor intensity of the evaluation of structures for manufacturability, regardless of the stage of their creation, and reduce the costs and time of technological preparation for the first time developed products.

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