Automation of the Synthesis of New Design Solutions Based on the Requirements for the Functionality of the Created Object

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Abstract. A modification of the method of information formalization on the composition and structure of a product at the stage of conceptual design is proposed in this article. The essence of the modified method is the application of technical solutions for the simultaneous implementation of several functions, which provides expansion of the possibilities for design changes or the creation of a new product. It is proposed to manage the synthesis of structures of new products with a given functionality based on setting the degree of fulfillment of several by each structural subsystem in the product; an indication of the probabilities of the appearance of structural elements in the product; setting the rules for describing the spatial position of these elements and using a matrix of unacceptable types of connections between them in the product. This matrix allows us to accumulate experience in the analysis of design results and is practically a limitation in the subsequent generation of connections between structural elements in new solutions. The application of these features makes it possible to create a model of preferences and limitations for a designer when creating new objects.

Keywords: conceptual design, technical solutions, system functions, structural elements, design stages

1 Introduction

The design process consists of some steps that are carried out with the support of various design automation systems. The degree of automation of these stages and support is different, depending on the type of stage and the required intellectual contribution of the designer to the stage. As a rule, designing consists of the stages of conceptual designing, creating a geometric model, performing strength, kinematic, dynamic and special calculations, technological analysis, and product control [1].

At the initial stage of design, the development goal and requirements for the design object are formulated [2]. Then the system functions that ensure the achievement of the goal are determined [3]. These are the least formalized stages of the development of objects, requiring experience, intuition, and creative input from project developers. Errors at these stages can lead to significant costs for correcting the situation or even closing the project [4, 5].

From the totality of tasks that are solved during the development of a new product, the most formalized are the stages that are implemented after the development of a geometric model, which creates the basis for further calculations, modeling the behavior of an object in various conditions.

Computer-aided design systems were developed for them, that solve problems at the stages of constructing a geometric model of parts and assemblies, creating parametric models, implementing technological control of the geometry and other stages before manufacturing the product [2, 3].

2 General statement of the problem

Variants of technical solutions are presented as a combination of various technical methods for implementing the functions necessary for the working of the object. The solution option is described as a set of structural elements for performing functions. The general idea of the design task of a technical system can be written down by the system:

$$TS = \langle F, K, S \rangle ,$$

where $F = \{F_1, \dots F_n\}$ – a set of basic functions of the created object;

$K = \{K_1, \dots K_m\}$ – an array of technical solutions (structural elements);

$S = \{s_{ik}\}_{m \times m}$ – a matrix of interactions between structural elements. It is assumed that $s_{ik} = 0$, if interaction is impossible and for everyone there is at least one $i, (i \neq k)$, for which $s_{ik} \neq 0$.

3 Work related analysis

The design process in modern technologies is based on the creation of a digital product model that accompanies it at all stages of the life cycle [6]. Besides, a multi-level process model is used with a cyclic repetition of the stages of development, testing, and verification until the requirements formed at the initial design stage are achieved. Such a process can significantly reduce design time and risks while improving the quality of the final product, which will make it more popular for the client. The fundamental difference from the approach of previous generations is the division into high-level and low-level architectures with the possibility of cyclically repeating the steps of each level of the architecture when it detects a mismatch with the initial requirements. The development of new technical solutions includes the following steps:

- formation of product requirements;

- functional analysis of the product;
- logical design with the decomposition of the product into structural elements and definitions of their functions;
- simulation mathematical modeling;
- building a geometric model;
- simulation of the developed product in various modes;
- testing of prototypes to verify the required performance.

Almost all existing methods for solving inventive problems contain the stage of expanding the design space [7 – 10]. In this case, the use of morphological analysis is effective.

A major role in the rapid development of the product is played by the possibility of using the developed mathematical apparatus. Automated tools for constructing simulation models of the varying complexity systems behavior for modeling mechanical, thermal, electrical, optical, and other systems with the replacement of physical modeling with many virtual models are implemented for this [11].

In modern procedural models for the conceptual design stage, the synthesis of new technical solutions at the stage of creating a high-level system architecture is based on determining the relationships of the development goal, which are carried out to achieve the functions, many technical solutions and signs of evaluating their quality under given conditions [2]. Information on the composition and structure of technical solutions at the stage of conceptual design can be represented in the form of project trees, graphs. A diagram of the relationship of the object, purpose, and functions performed is shown in Figure 1.

Each system is created to achieve a given goal. To achieve this goal, the object must perform several functions that are allocated when the goal is decomposed. To perform the specified functions, the object contains several structural elements in the form of assembly units and parts. In the process of decomposition of the object, a tree of structural elements of the product is created that represents the composition of the object. To obtain the structure of an object, it is considered as a system in which structural elements are interconnected to ensure the joint performance of these functions [12, 13].

The choice of options is based on the analysis of indicators for the elements of the system and its assessment as a whole based on various models [14, 15, 16]. After evaluating and choosing an object layout option, ideographic models of the structure are constructed from the selected parts (schemes with different conditional, symbolic representations of the elements that make up the nodes and connections of the graph). Analogs can be diagrams of components deploying UML [17].

Part of the stages of designing technical objects before building a geometric model is automated. However, these steps begin at the level where you can create a mathematical model of the structure or process that models the physical processes in the system. On its basis, the construction of a geometric model of the designed object is carried out, which is used for further analysis.

At the same time, the stages of the formation of a conceptual model, technical solutions for elements and the structure as a whole today do not have developed automation systems. These stages require the realization of creative potential and the intellectual contribution of developers to the scheme of the created object. Therefore, recently, interest in methods for solving creative engineering problems has grown significantly [12, 13, 14]. Existing developments for the search for new ideas are based on the application of methods to increase the creative activity of engineers, identifying and eliminating technical contradictions [15], using the fund of techniques and physical effects, etc. Thus, in [12] the authors propose using artificial intelligence techniques in the form of knowledge bases. Heuristic algorithms are used to generate and select optimal constructs in the process of component-based engineering design [18]. It is important to establish interaction between the developer and the tool of computational synthesis during conceptual design [14], to create a model of designer preferences for searching in the space of technical solutions to the best projects.

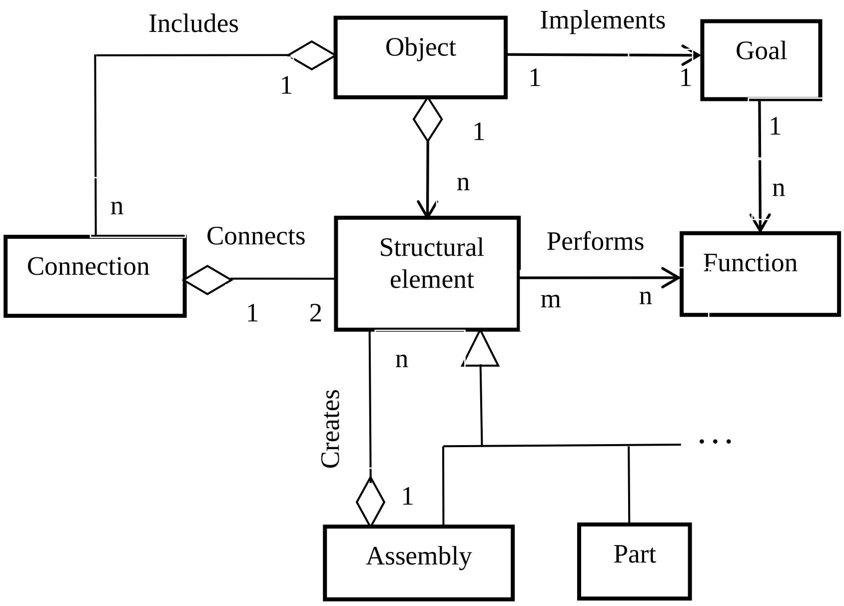


Fig. 1. The relationship between the functions and structure of the product during the conceptual design stage

The associated execution of functions in the process of achieving the goal forms the behavior of the object, which, for example, can be represented in the form of a state diagram [17]. The operating conditions of the system act as restrictions on the technical decisions made. To establish these relations and evaluate their significance, one can use expert estimates, accumulated economic data, and designer preferences. The authors create rules that describe the dynamics of objects based on cyclograms of their work and/or expert knowledge. In the study [13], a set of computational tools was developed those help designers to solve the problem of navigation in the design space. The presented methodology is based on the automation of the functional synthesis paradigm by combining various computational methods. The implemented system provides a method for automatically generating new alternative solutions to real design problems.

Thus, in addition to the structure of the product in the form of interconnected structural elements, tools are also needed to describe the behavior of the products during operation for changing states, as well as the behavior of the system elements in time during the execution of the specified functions.

Modern products typically include several heterogeneous subsystems based on various physical principles. Therefore, the allocation of aspects of the consideration of the system (mechanical, electrical, thermal, chemical, others) and the implementation of technical solutions for each highlighted aspect is effective in the development of the product. The highlighting of aspects allows you to decompose the designed object following the physical principles within which subsystems work, and perform design separately for each aspect. Monitoring the completeness of the solution to the problem in each aspect can be performed based on different flowcharts [17, 19].

The structure as a whole, its elements, and relationships in the process of choosing technical solutions are mapped on the elements of the geometric model of the system that is created in the CAD system. This process is based on the analysis of properties and estimates of technical solutions accumulated in the databases that are used to implement the functions selected at the previous stage [13]. In this case, the information is presented in the form of a matrix of functions and adopted technical decisions. To display the structure of the designed object, the adjacency matrix is used in which the structural elements of the system and their relationships are shown.

In the process of constructing a geometric model of a product in a CAD system, not only structural elements are displayed, but also their relationships (Fig. 2), taking into account accepted abstractions, methods, and features of representing the geometry of elements in a particular CAD system.

This work requires considerable time and other resources; therefore, an error at the stage of choosing the product structure and its structural elements leads to significant costs for the subsequent reconstruction of the geometric model.

4 A modified method of conceptual design

The goal of this work is to propose a method for presenting a model of a technical system based on the use of effective approaches to solving problems of conceptual design. The essence of the methodology is the use of technical solutions for the simultaneous implementation of several functions and providing the ability to control the generation of structures of new products with a given functionality. This is because the development of effective designs is usually carried out through the combined use of various subsystems in which the elements perform several functions necessary for the operation of the product as a whole.

Then the general description of the system will take the form:

$$TS = \langle F, K, S, V, Sd, P \rangle ,$$

where the structural element K_i can implement one or more functions F_j;

$F = \{F_1, \dots F_n\}$ – a set of basic functions of the created object (for example, for face milling cutter it will be: basing of a cassette in a milling cutter body, fastening of a cassette in a milling cutter body, etc.);

$K = \{K_1, \dots K_m\}$ – an array of technical solutions (structural elements – basing of a cassette on a groove, basing on a groove through the managed element, basing through an indexing insert, etc.);

$V = \{v_{ij}\}_{n\times m}$ – the matrix of implementation levels of a number of functions by technical solutions. Elements of the matrix take values from 0 % to 100 %. For each structural element K_i and function F_j, there is at least one $v_{ij} \neq 0$.

$Sd = \{sd_{ik}\}_{m\times m}$ – the matrix of unacceptable interactions between structural elements. It is assumed that $sd_{ik} = 0$, if interaction is impossible.

$P = \{p_i\}_m$ – probabilities of occurrence of structural elements in the product that can be assigned by experts or designers.

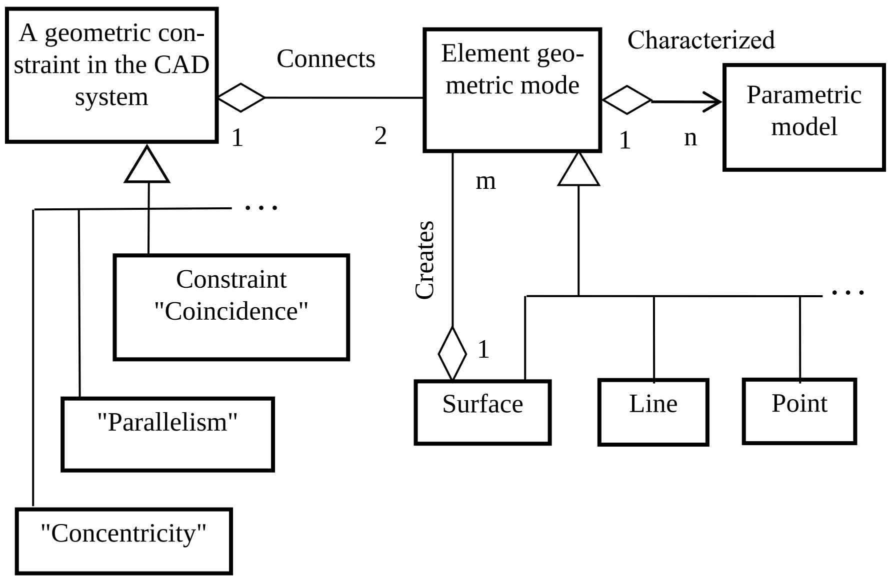


Fig. 2. Scheme for representing a geometric model of a structure in a CAD system

Studies by several authors show that to create a new system design, it is necessary to represent its structure as a set of structural elements as subsystems of elements with their connections. This creates a certain redundancy of information within the system representation, but just such an approach allows expanding the search space for technical solutions and also provides a more detailed description of the object.

In this work, the task of creating an algorithm that would allow us to synthesize new designs without preliminary expert evaluation of the elements was solved. Such an algorithm should be relatively simple, provide a step-by-step design process, provide an opportunity to expand the search space for solutions, control the direction of the search for the desired system structure, formalize the product description, give a visual representation of the synthesized mechanism, accumulate information about the permissible relationships of structural elements to increase the efficiency of subsequent decisions. The design results with this approach can be used to assess the influence of structural elements and their interconnections on the achieved goals, capabilities, and features of the resulting structures.

After analyzing the requirements for the designed system and highlighting the functions that the created object should perform, it is necessary to establish the presence of various subsystems that will provide the necessary functionality of the created product. As a rule, this is the task of experts in several subject areas, because modern products include subsystems that use various physical principles for their work. The structure of the presentation of information for the selection of technical solutions for system functions is shown in table 1.

Table 1. The structure of the presentation of information for the selection of technical solutions for given product functions

Technical solutions	Functions and degree of their implementation by technical solutions, %					The probability of using a technical solution in the construction of an object
	F_1	F_2	…	F_{m-1}	F_m	
$\{K_1\}$	100	60		100	100	p_1
$\{K_2\}$	100	30		45	0	p_2
…	...	…	v_{ij}	…	...	…
$\{K_n\}$	100	100		0	20	p_n

The choice of structural elements from the list of known technical solutions in the presence of expert' or other assessments does not present special difficulties when implemented on a computer. Of interest is the realization of the possibilities of combined use of technical solutions that can combine the performance of a number of functions and thus increase the efficiency of design decisions. For this, technical solutions are presented as a subsystem of elements interconnected. Moreover, one can consider the purpose of individual elements not only in the subsystem but also in the possibility of application in other subsystems. For example, a typical function of individual elements in subsystems is the connection of two subsystems with each other. For this, the table indicates that each technical solution can implement several functions but to a different degree. For example, if an element of a subsystem is a base for attaching other elements, then it can provide services for attaching elements of another or several other subsystems, i.e. performs functions for two or more related design solutions.

The description of the design object in table 1 is insufficient because there are no indications of the relationship between the technical means of implementing the functions that form the structure of the product. At the same time, a new technical solution can be the result of not only the choice of new means of implementing functions but also a new set of relations between these elements. Therefore, in this paper, we consider a part of the algorithm associated with the presentation of information and the formation of matrixes for the description of the designed product. In particular, the graph of the system structure is represented in the form of the adjacency matrix S, which includes a set of elements and their connections.

One of the issues of the effectiveness of this algorithm is the allocation of a subset of implemented solutions. This is done in two ways. First, matrixes of unacceptable interactions *Sd* are introduced that exclude impossible combinations of elements and their relationships. Secondly, the presence of elements and their interactions is limited by setting the probabilities of their occurrences in a particular task.

This allows you to control the search process in the search space of technical solutions. To do this, you can set the degree of implementation of a number of v_{ij} functions by each technical solution in the product. For example, setting the degree of implementation of the fastening function of the elements to one of the structural solutions, the value $v_{ij} = 100\ \%$, you can take this as the basis for the structure as a whole. In addition, the specification of restrictions on the presence of elements and their interactions is determined by indicating the probabilities of their appearance in the structure of the product. In particular, a specific technical solution can be fixed in the composition of the product by setting the probability of its occurrence during generation: $p_i = 1$.

Experts may be involved in assigning degrees of implementation of functions and probabilities. However, a preliminary assessment of the impact of each technical decision on the implementation of several functions is a complex task that requires analysis of a large amount of information. Therefore, in the first stages, in our opinion, it is better to apply the trial and error method for the synthesis of structures and perform subsequent analysis of the results of the generation of solutions. This provides information for studying the features of the designed product and allows you to accumulate unacceptable types of connections between structural elements in the *Sd* matrix and thus form a model of designer preferences. This matrix is practically a limitation in the subsequent generation of the types of connections of technical solutions in a new product. In turn, a change in connections can significantly change the structure of the system.

Thus, the essence of the developed algorithm consists of the combined implementation of the basic functions of the created object, which is ensured by the technical execution of its elements and their relationships. For each function, a search is made for options for technical solutions of elements that are considered as subsystems of elements, ensure its implementation and at the same time support the implementation of other functions.

An important issue is the determination of the description of the spatial position of the structural elements of the subsystem: one above or below the other, concentric, etc. In addition to changing the probabilities of their application and interconnections, one can vary the relative spatial position of these elements and obtain various solutions. This is achieved by setting the rules for traversing the structure, for example, from bottom to top, from outside to inside, etc. Without the introduction of such rules, unambiguous description of objects is impossible. Consequently, subsequent object recognition, search for analogs, and comparison with existing design options are complicated. For this, a partial order relation is defined on the set K, which defines restrictions on the spatial order of the spatial position of the structural elements of the subsystem.

A partial order relation is often represented as a digraph (acyclic, anti-transitive). The direction of movement can be determined by a variety of probabilities or by setting the rules for bypassing a structure (Fig. 3).

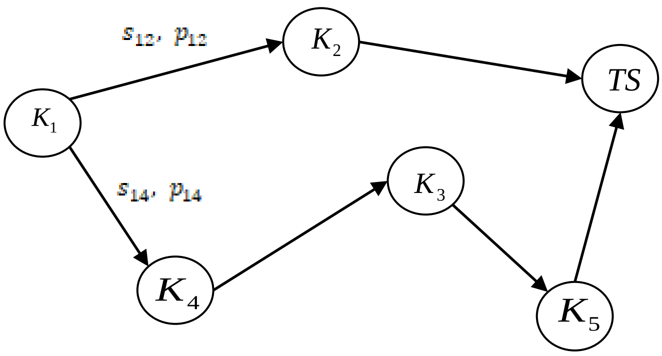


Fig. 3. Digraph

The vertices of a digraph are elements K_i. Ribs connect the vertices if $s_{ik} \neq 0$. When using many probabilities, the direction is selected by $p = \max\{p_i\}$.

The process of obtaining one technical solution can be presented in the form of a cyclogram (table 2).

To simplify the task, a phased analysis of the subsystems that make up the object is carried out. In this case, the task for the system is reduced to a series of similar procedures for subsystems of elements.

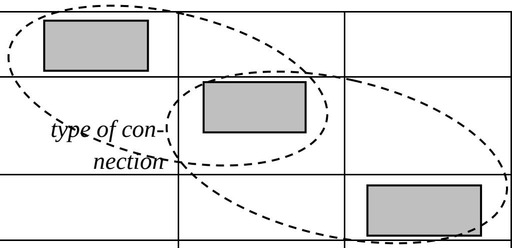
This corresponds to the process of object decomposition [17]. Otherwise, the presentation of the system will be either not flexible enough, or the number of solutions will unreasonably increase.

The analysis of a number of objects as systems of functional elements showed that in some cases, with a reasonable restriction on the list of means of performing functions, their graphical representation can be relatively simple. This is also facilitated by the simplification of the graphical representation of the structures of elements, images of the connections between them, which allows one to obtain schemes of the considered subsystems and the object as a whole.

For a more flexible graphical representation of the subsystems, they are also divided into elements; the connections between them are fixed. Despite the increase, in this case, the total number of elements, the simplification of the graphic image is achieved by highlighting the repeating structural elements and setting their relative position in the graphic image.

This can be automatically performed for a given order of the spatial description of the structure.

Table 2. The process of obtaining one technical solution

Technical solutions	Assembly scheme (sequence)			
$\{K_1\}$				
$\{K_2\}$	*type of connection*			
$\{K_3\}$				
…				…

The connection functions of subsystems need to be allocated separately to address the issue of the integrated application of design solutions. This will help to focus on solving such issues and find the appropriate spatial arrangement of structural elements for this.

If the system includes several heterogeneous subsystems, then the construction of a common table “function - technical solution” allows in this case to provide a graphical representation of the object for discussion and sequential solution of the design problem, creating the composition and structure of the object. At the same time, a phased solution of problems for the product subsystems is carried out and the possibilities of implementing functions by the selected elements of the subsystems are considered.

This creates the possibility of combined solutions. For example, one of the structural elements provides space for the placement of elements of other subsystems. Elements that provide the perception of mechanical loads can simultaneously protect against heat generated in the object or passing electric current in the product.

Evaluation of each technical solution is an expert assessment of the degree of its effectiveness. The total product rating is defined as the sum of the ratings of all technical solutions, related to their number:

$$O = \sum_i \sum_j v_{ij} \cdot O_i / n,\ j = 0 \ldots m,$$

where O – an overall product rating, O_i is an expert assessment of the degree of efficiency of the i-th technical solution, n is the number of technical solutions, m is the number of functions.

Moreover, the sum of the degrees of fulfillment by all technical solutions of each function should not be less than a given threshold value.

$$V_i \geq \sum_i v_{ij},\ i = 0 \ldots n.$$

This value may be less than 100%, taking into account the subsequent modification of the design of the product.

5 Case study

As an example, consider part of the design process of a face milling cutter with exchangeable cassettes. With increasing depth of cutting, the components of the cutting forces increase sharply in all three directions: radial X, tangential Y, and axial Z. At the same time, the importance of such a design parameter as vibration resistance increases. It can be provided by performing the functions of a division of cut area by thickness and width. In addition, the function of basing and attaching a cassette with a cutting insert in the milling cutter body is important. Each of the above functions can be implemented by several variants of technical solutions presented in table 3.

The table does not show the probabilities of the occurrence of technical solutions in product P, because they are accepted the same for them. It should also be noted the conditions for the formation of a matrix of unacceptable options for the joint application of technical solutions Sd: technical solutions 1,2,3 and 4, as well as 5 and 6, cannot be used together, although 5 and 6 solve the problem of dividing the cut area. Technical solutions 7 and 8, solutions 8 and 9, as well as 12,13 and 14 ($sd_{ik} = 0$ for these cases), cannot be used together too.

The analysis of well-known constructions of face milling cutters showed that milling cutters are most widespread without the division of the cut area: technical solution A (3, 5, 7, 10, 11), and on the axis of Y inhaling is not provided. For the constructions of milling cutters with the division of cut area, base decisions can be B (1, 6, 7, 10, 11) or C (1, 6, 8, 11, 13). Coming from the data-driven to the table 3, at the planning of knot of the setting of cassettes with an indexing insert in the body of face milling cutter, it is expedient to use next new constructions: the decision of D (2, 7, 9, 14) and the decision of G (2, 8, 14).

Table 3. The structure of the presentation of information for the choice of constructive solutions of the cassette assembly of the milling cutter

i	Technical solutions (TS) K_i	Evaluation TS	Functions and degree of their implementation by technical solutions, %							
			The division of the slice		Axis-based cassettes			Axis cassettes mounting		
			in width	by thickness	Z	Y	X	Z	Y	X
1	Stepwise placement of the inserts, the side cutting edge angle is the same	8	100							
2	Stepwise placement of the inserts, the side cutting edge angle is different	10	100	90						
3	Placing the inserts in one row, the side cutting edge angle is the same for adjacent inserts	5		50						
4	Placing the inserts in one row, the side cutting edge angle for adjacent inserts is different.	7	90	90						
5	Mill body with even pitch of cassettes	5	50							
6	Mill body with a differential pitch of cassettes	6		100						
7	Mill body with through grooves	9				100	100			
8	Mill body with closed grooves	6			100	100	100			
9	Mill body with an annular recess	10			100					
10	Insert tightening screw	6			100		100			
11	Axial screw cassette	5						100		100
12	Front wedge cassette	8							100	100
13	Cassette with wedge screw	9							100	100
14	Cassette with wedge screw and axial tilt	10						100	100	100

Calculation of estimates of the received designs of cutters:

$$A:(5\cdot 50+5\cdot 50+9\cdot 100+9\cdot 100+6\cdot 100+5\cdot 100+5\cdot 100)/5=780.$$

$$B:(8\cdot 100+6\cdot 100+9\cdot 100+9\cdot 100+6\cdot 100+5\cdot 100+5\cdot 100)/5=960.$$

$$C:(8\cdot 100+6\cdot 100+6\cdot 100+6\cdot 100+6\cdot 100+5\cdot 100+5\cdot 100+9\cdot 100)/5=1020.$$

$$D:(10\cdot 100+10\cdot 90+9\cdot 100+9\cdot 100+10\cdot 100+10\cdot 100+10\cdot 100+10\cdot 100)/4=1925.$$

$$G:(10\cdot 100+10\cdot 90+6\cdot 100+6\cdot 100+6\cdot 100+10\cdot 100+10\cdot 100+10\cdot 100)/3=2233.$$

Thus, the application of perspective technical decisions with a high expert estimation and implementation by them several functions allows designers to get new effective decisions. In this case, an example of the development of milling cutters is made with the division of the cut area due to the step placing of indexing inserts under different corners, and also with the use of fastening of a cassette to the mill body by a wedge screw and axial tilt 14. The application of such structural decisions allows substantially to increase the estimation of a milling cutter.

The mill body with a differential pitch of cassettes 6 provides performing the function of a division of the cut area by thickness on 100% but is difficult to manufacture, as well as the use of closed grooves for installing of cassettes 8.

6 Conclusion

The choice of structural elements for the system based on the accumulated base of technical solutions, if the ratio of function and design is one to one, in most cases allows you to quickly assemble the product, go to the graphic model in the CAD system. Nevertheless, this does not ensure the creation of a new design, which has a significant novelty about analogs.

A significant change or creation of a new design is made if the structural element performs functions for several product subsystems at the same time. The transition to the consideration of a structural element as a subsystem, consisting of a set of elements, significantly expands the search field and allows you to highlight the elements that are important for the set of product subsystems. For example, an element can provide a connection of subsystems in a single design. Thus, the elements can be considered in terms of the ability to perform several functions in the product.

The application of this technique allows designers in the process of conceptual design to structure information on product design, to perform a phased solution to the problem, considering the combined use of various subsystems. The sequential implementation of the stages provides a deeper understanding of the emerging problems of creating a new object, increases the creative activity of engineers. Analysis of the results of test synthesis of structures based on the matrix "function - technical solution" and given estimates of the technical solution of several functions allows you to gradually accumulate information about unacceptable options for the connections of structural elements. The use of additional adjacency matrixes, in which unacceptable variants of structural solutions are accumulated, ensures the preservation of design experience and the designer's preferences. Managing the automatic generation of decisions based on changes in the probability of the appearance of elements and the degree to which they perform functions allows you to automatically construct designs with control of the identified constraints.

The use of the modified conceptual design method allows the formation of a formalized description of the design to enable the subsequent application of optimization methods, for example, a genetic algorithm [20]. To increase the effectiveness of the application of such methods, in addition to the procedure for assessing the quality of a design solution, it is important to manage the search in the space of design solutions and to set restrictions for choosing valid options. This approach can be effectively used for training designers, identifying relationships between functions, technical implementation, and the purpose of the resulting object, regardless of the degree of automation. The application of the algorithm is demonstrated by the example of designing a tool for milling.

References

1. INCOSE Systems Engineering Handbook. A Guide for System Life Cycle Processes and Activities. Wiley, New Jersey (2015).
2. Weilkiens, T., Lamm, J.G., Roth, S. et. al. Model-Based System Architecture. Wiley, New Jersey (2015).
3. Myrup Andreasen, M., Thorp Hansen, C., Cash, P. Conceptual Design: Interpretations, Mindset and Models. Springer International Publishing, Cham (2015).
4. Ajoy Kumar Kundu, Mark A Price, David Riordan Conceptual Aircraft Design. An Industrial Approach. Wiley, Croydon (2019).
5. Floridi, L.: The Logic Of Information: A Theory Of Philosophy As Conceptual Design. Oxford University Press, Oxford (2019)
6. Noël, F.; Roucoules, L.: The PPO design model with respect to digital enterprise technologies among product life cycle. (2008)
7. Wolfgang Ernst, E. Theory of Technical Systems – Educational Tool for Engineering. Universal Journal of Educational Research, 2016, vol.4(6), pp. 1395–1405 (2016) DOI: 10.13189/ujer.2016.040617
8. Ritchey, T.: General morphological analysis as a basic scientific modelling method. Technological Forecasting & Social Change, 2018, vol.126, pp. 81-91. (2018) DOI: 10.1016/j.techfore.2017.05.027
9. Álvarez, Asunción, and Tom Ritchey. "Applications of general morphological analysis." Acta Morph. Gen 4.1 (2015).
10. Kuznetsov, Yu.M., Prydalnyi, B.I.: Proektuvannia tsilovykh mekhanizmiv manipuliuvannia verstativ novoho pokolinnia: Navch. Posibny`k. Lutsk,: Vezha-Druk, (2014)
11. Fritzson, P.: Principles of object oriented modeling and simulation with Modelica 3.3: a cyber-physical approach. Wiley-IEEE Press, (2015)
12. Latyshev, A.V., Romakin, V.A., Hachumov, V.M. et. al.: Metody i modeli avtomaticheskogo sinteza tehnologicheskih processov, osnovannogo na znanijah. Programmnye sistemy: teorija i prilozhenija, vol.7:3(30), pp. 25-43. (2016)

13. Kurtoglu, T., Swantner, A., Campbell, M. Automating the conceptual design process: “From black box to component selection”. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, vol. 24(1), pp. 49-62. (2010) DOI:10.1017/S0890060409990163
14. Kurtoglu, T., Campbell, M.I. An evaluation scheme for assessing the worth of automatically generated design alternatives. Res Eng Design, vol.20, pp. 59–76 (2009) DOI: 10.1007/s00163-008-0062-1
15. MO, Zhen-chong & GONG, Lin & WANG, Jin-yi & GAO, Jun.: Construction and Application of Product Fast Conceptual Design Knowledge Base Based on Configuration Flow Graph. DEStech Transactions on Engineering and Technology Research. (2020) DOI: 10.12783/dtetr/acaai2020/34187
16. Draghici, G., Banciu, F.V.: Development of a conceptual design methodology for products. In: International Conference on Manufacturing Systems ICMaS 2004, Bucharest, 7th-8th October 2004, pp. 575-578 (2004) DOI: 10.13140/2.1.4537.7920
17. Desfray, P., Raymond, G.: Modeling Enterprise Architecture with TOGAF. A Practical Guide Using UML and BPMN. Elsevier, Waltham (2014)
18. Wang, J., Terpenny, J. Interactive evolutionary solution synthesis in fuzzy set-based preliminary engineering design. Journal of Intelligent Manufacturing volume 14, pages153–167 (2003).
19. Fan, Z.; Wang, J. & Goodman, E. / Exploring Open-Ended Design Space of Mechatronic Systems. International Journal of Advanced Robotic Systems, Volume 1, Number 4 pp. 295 - 302(2004). ISSN 1729-8806. https://doi.org/10.5772/5636
20. Bohdanova, L.M., Vasilyeva, L.V., Guzenko, D.E. et al. A Software System to Solve the Multi-Criteria Optimization Problem with Stochastic Constraints. Cybern Syst Anal 54, 1013–1018 (2018). https://doi.org/10.1007/s10559-018-0104-2