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ALGORITHMS FOR SYNTHESIS OF TECHNOLOGICAL OPERATIONS FOR MANUFACTURING SAMPLES OF STRUCTURALLY COMPLEX PRODUCTS

ALEXANDER V. PETUKHOV

Sukhoi State Technical University of Gomel (Gomel, Republic of Belarus)

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Abstract. The aim of the study is to develop a mathematical model for the synthesis of technological operations in the structure of algorithms for a system of automated design of technological processes. When solving the problem of synthesis of technological operations in the structure of algorithms of the automated design system of technological processes for manufacturing prototypes of structurally complex products, the following algorithms are used: solving the direct choice problem; formation of a set of possible alternatives; checking possible alternatives for admissibility; formation of a set of acceptable alternatives; determining the set of desired typical technological solutions and optimizing the choice of solutions. A block diagram of the system of algorithms for the process of synthesis of technological operations, based on a combination of individual and standard technological solutions in the design of technological processes for the experimental production of prototypes of structurally complex products, has been obtained.

Keywords: synthesis problem, technological operations, structurally complex products, modeling of decision making.

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АЛГОРИТМЫ СИНТЕЗА ТЕХНОЛОГИЧЕСКИХ ОПЕРАЦИЙ ИЗГОТОВЛЕНИЯ ОПЫТНЫХ ОБРАЗЦОВ СТРУКТУРНО-СЛОЖНЫХ ИЗДЕЛИЙ

А. В. ПЕТУХОВ

Гомельский государственный технический университет имени П. О. Сухого
(г. Гомель, Республика Беларусь)

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Аннотация. Разработана математическая модель синтеза технологических операций в структуре алгоритмов системы автоматизированного проектирования технологических процессов. При выполнении данной задачи в случае изготовления опытных образцов структурно-сложных изделий используются алгоритмы: решения задачи прямого выбора, формирования множества возможных альтернатив, проверки возможных альтернатив на допустимость, формирования множества допустимых альтернатив, определения множества искомых типовых технологических решений и оптимизации выбора решений. Получена структурная схема системы алгоритмов процесса синтеза технологических операций на основе сочетания индивидуальных и типовых технологических решений при проектировании технологических процессов экспериментального производства опытных образцов структурно-сложных изделий.

Ключевые слова: задача синтеза, технологическая операция, структурно-сложное изделие, моделирование принятия решений.

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Introduction

When creating a new product, a special place is occupied by the production of a prototype. This process completes the design development of the product. After it, the technological preparation of serial production begins [1]. Increased competition among developers and manufacturers of high-tech modern equipment demonstrates examples of a significant reduction in the production time of a prototype of a structurally complex product. The study of the functional structure of the system of technological preparation for the production of prototypes [2] shows that the most significant time is spent on the design of technological processes. This circumstance served as motivation for studying the problem of synthesizing technological operations in the structure of algorithms for the automated design of technological processes for manufacturing prototypes of structurally complex products.

The use of the theory of choice and decision making in the synthesis of rational options for technological operations in the production of prototypes of structurally complex products makes it possible to determine the following system parameters:

– composition and structure of system algorithms;
– input and output data of algorithms;
– reference data of the system;
– interconnection of system algorithms.

In the theory of choice and decision making, a formal description of the decision problem is expressed by the formula

$$\langle \Omega_A, PO \rangle, \tag{1}$$

where Ω_A is represented by many possible solutions (alternatives); PO is the principle of optimality, allowing one to choose the best solutions [3].

The solution of problem (1) showed that the following algorithms are needed to automate the synthesis of technological operations under the specified conditions:

– solution of the problem of direct choice;
– formation of a set of possible alternatives Ω_P;
– checking possible alternatives for admissibility;
– formation of a set of feasible alternatives Ω_D;
– determination of the set Ω_{r_T} of required typical technological solutions;
– optimization of the solution choice [4].

The aim of the study was to develop a block diagram of a system of algorithms for the process of synthesis of technological operations based on a combination of individual and standard technological solutions in the design of technological processes for the experimental production of prototypes of structurally complex products.

Algorithms for solving the problem of direct choice and the formation of a set of possible alternatives

The mathematical expression of the PO optimality principle is the selection function C_{PO}, and the solution to problem (1) is a subset Ω_{PO} of the set of alternatives Ω_A, i. e. $\Omega_{PO} \subset \Omega_A$; while $C_{PO}(\Omega_A) = \Omega_{PO}$. To apply problem (1) and methods for its solution to the choice of typical technological solutions, depending on the previously made individual decisions, first of all, it is necessary to determine the set of alternatives Ω_A.

In the general case, all possible complete technological solutions r with fixed, i. e. individual technological solutions specified by the technologist $r_I^{'} : r = \left(r_I^{'}, r_T\right)$ are fed to the input of the process of making technological decisions [5]. For the technological process being designed, from all solutions r submitted to the input of the technological decision-making process, only those are selected for which the condition is satisfied $r_T = f\left(r_I^{'}\right)$. Since the decisions $r_I^{'}$ are fixed for each designed technological process, then in fact these decisions are fed to the input of the technological decision-making process, and the set of typical technological solutions R_T is a set of alternatives $\Omega_A = R_T$.

To ensure the solvability and reduce the complexity of solving problem (1), as well as to reduce the time of searching for solutions, it is necessary to perform a phased narrowing of the search area. To do this, on the set Ω_A, a set of possible $r_I^{'}$ alternatives Ω_P is allocated. Then, on the set Ω_P, the set of feasible alternatives Ω_D is allocated, which constitutes the desired set of alternatives. At the same time, $\Omega_P \subset \Omega_A$ $\Omega_D \subset \Omega_P$, the sequential selection of sets Ω_P and Ω_D from the set of alternatives Ω_A becomes possible after a specific solution $r_I^{'}$ is received at the input of the system. In this case, two selection problems arise: which constitutes the desired set of alternatives:

$$\langle \Omega_A, PO_1 \rangle; \tag{2}$$

$$\langle \Omega_P, PO_2 \rangle. \tag{3}$$

The solution to problem (2) is the set Ω_P, and the solution to problem (3) is the set Ω_D of alternatives, of which as a result of solving the problem

$$\langle \Omega_D, PO_3 \rangle \tag{4}$$

the desired typical technological solution $r_T^{'}$ is determined that satisfies the condition f for a given $r_I^{'}$.

In the general case, the solution to problem (4) may turn out to be not one, but a number of solutions $r_T^{'}$, which will make up the set $\Omega_{r_T} : C_{PO_3}\left(\Omega_D\right) = \Omega_{r_T}$. Then, in order to identify one (optimal) solution $r_T^{'}$ it is necessary to solve the problem

$$\left\langle \Omega_{r_T}, PO_4 \right\rangle. \tag{5}$$

Since in this case it is possible to provide all sets Ω_{r_T} (for example, sets of similar drills, gauges, etc.) and formulate in advance the optimality principle PO_4 for all $r_T \in \Omega_{r_T}$, task (5) will be an optimization problem. Let us explain the above with a specific example. Suppose that it is necessary to develop a technological process for manufacturing a part. The result of choosing the type of production of the part from the existing alternatives (casting, forming, machining, welding, etc.) depends on the configuration, material and production volume of the part. Suppose that the technologist has made a directive decision to manufacture the part by machining. This is a prior individual decision $r_I^{'}$. It defines the set of existing alternatives Ω_A as a complete set of existing machining operations. This set constitutes a set of typical technological solutions R_T, which in this case is a set of alternatives $\Omega_A = R_T$. The gradual narrowing of the search area occurs when taking into account the specific composition of the factory equipment. At the same time, on the set Ω_A, a set of possible operations for manufacturing the part Ω_P is distinguished. Definition of valid alternatives Ω_D, i. e. the set of operations that make up the desired set of operations (screw-cutting operation, CNC turning operation, etc.) is determined by comparing the parameters of the part (overall dimensions, machining accuracy, annual output) with the technical characteristics of the machines on which a particular operation is performed. If there are several feasible alternatives Ω_D, then it is necessary to use the previously formulated principle of optimality. In this case, alternatives Ω_D can be evaluated at the minimum cost per hour of work to operate the machine to perform the operation.

One of the features of the computer-aided design of technological processes, which implements the method of combining solutions, is the ability of the technologist to directly set standard technological solutions, which are conveniently called directive. The need to specify directive technological solutions may, for example, arise in the development of technological processes that require the use of a special tool in certain operations that is not in the regulatory and reference base of the system.

Let us designate the set of directive technological solutions as R_{Dir}. Then problem (1) is a direct choice problem if for the considered transition (operation) the typical solution $r_T^{'}$ is contained in R_{Dir}, i. e. $r_T^{'} \in R_{Dir}$. In this case, the solution to problem (1) is the typical solution $r_T^{'} : C_{PO}\left(\Omega_A\right) = \left\{ r_T^{'} \middle| \forall r_T^{'} \in R_{Dir} \right\}$ given by the technologist. In this case, there is no need to solve problems (2)–(5).

The input data of the algorithm for solving the direct choice problem are the elements of the set R_{Dir} of directive decisions. The output of the algorithm is the elements of the set $C_{PO}\left(\Omega_A\right)$, i. e. typical technological solutions specified in this case by the technologist-user of the system. At the same time, it is advisable to arrange the set R_{Dir} in the form of the initial data of the system, adding to it all the individual decisions of the technologist, adopted by him for this technological process. Then the functional purpose of the algorithm under consideration will be the selection of explicitly specified standard technological solutions from the entire flow of initial data of the system.

If absent in R_{Dir}, i. e. in the initial data of the system, standard technological solutions or when they are exhausted, i. e. when the condition $\neg\exists r_T^{'} \in R_{Dir}$ for the next transition of the technological operation is met, control is transferred to the algorithms for generating the desired set of alternatives. Following formula allows us to present an algorithm for generating a set of possible alternative solutions:

$$C_{PO_1}\left(\Omega_A\right) = \Omega_P^{r_{me}} \bigcup \Omega_P^{r_{cut}} \bigcup \Omega_P^{r_{aux}} \bigcup \Omega_P^{r_{meas}}, \tag{6}$$

where $\Omega_P^{r_{me}}$ is the name and model of the equipment; $\Omega_P^{r_{cut}}$, $\Omega_P^{r_{aux}}$, $\Omega_P^{r_{meas}}$ is the cutting, tool; measuring tools.

The input of the algorithm for determining possible solutions is the set R_{Dir} containing the solution r_{to} (operation name) represented as an operation code. For the functioning of the algorithm, a directory of operations is needed, in which each operation is associated with a certain type of equipment. The output of the algorithm is the elements of the set $\Omega_P^{r_{me}}$. Upon completion of the algorithm, control is transferred to the algorithm for determining transition texts.

The input data for determining codes of possible wordings of transition texts are descriptions of the surfaces to be machined and the selected type of cutting tool. When functioning, the algorithm uses a directory of parts surfaces, where a correspondence is established between the surface type and a possible transition code, and a cutting tool directory, in which a correspondence is established between the types of cutting tool and possible transition text wording codes. Further control is transferred to the algorithm for determining the admissible wordings of transition texts.

The input data for the algorithm for selecting possible types of cutting tools are the descriptions of the surfaces to be machined (when creating systems with graphical support), the text of the transition and the given model of the equipment on which this operation is performed. For the functioning of the algorithm, a directory of parts surfaces is required, in which each type of surface is associated with one or more specific types of cutting tools and an equipment directory, where each equipment code corresponds to certain types of cutting tools. The output of the algorithm is the elements of the set $\Omega_P^{r_{cut}}$ of possible types of cutting tool. Upon completion of the algorithm, control is transferred to the algorithm for determining the permissible types of cutting tool.

The input data for the algorithm for determining the possible types of auxiliary tool is the type of the selected cutting tool and the given equipment model. The algorithm works using a cutting tool directory containing the established correspondence between the types of cutting tool, auxiliary tool and equipment directory, which reflects the correspondence between the equipment model specified by the code and the types of auxiliary tools that can be installed on this equipment. The output of the algorithm is the elements of the auxiliary tool set $\Omega_P^{r_{aux}}$. Upon completion of the algorithm, it is advisable to transfer control to the algorithm for determining the permissible types of auxiliary tool.

The input data for the algorithm for determining possible types of measuring tools (when creating systems with graphical support) are descriptions of the surfaces to be machined, reflecting their shape, controlled dimensions and location relative to other surfaces of the part. For the functioning of the algorithm, a directory of parts surfaces is needed, in which certain types of measuring tools correspond to each surface type. For systems without graphical support, the input data can be a processed element and its characteristic. It is convenient to transfer further control to the algorithm for determining the permissible types of the measuring tool.

Algorithms for generating a set of feasible alternatives and determining the desired solutions

The solution of problem (3) – the set of feasible alternatives can be represented as

$$C_{PO_2}\left(\Omega_P\right)=\Omega_D=\Omega_D^{r_{me}}\bigcup\Omega_D^{r_{cut}}\bigcup\Omega_D^{r_{aux}}\bigcup\Omega_D^{r_{meas}}. \quad (7)$$

Formula (7) shows that the set Ω_D of feasible alternatives can be formed using four algorithms, each of which generates one of the following feasible technological solutions: $\Omega_D^{r_{me}}$ – equipment name; $\Omega_D^{r_{cut}}$, $\Omega_D^{r_{aux}}$, $\Omega_D^{r_{meas}}$ – cutting, auxiliary, measuring tools. Now let's consider a number of statements that are quite obvious from a technological point of view for the formation of a set of alternatives.

Statement 1. The permissible type of equipment corresponds to the name of the machine tool operation, i. e. r_{me}~r_{to}. If we denote the set of admissible types of equipment on which r_{to} operations are performed by Ω_D^{me}, then we can write

$$\Omega_D^{me}=\left\{\forall r_{me}\in\Omega_P^{me}\left|\theta_{me}^{r_{me}}=\theta_{me}^{to}\right.\right\}. \quad (8)$$

Statement 2. For processing in one transition a combination of surfaces of various shapes, such types of cutting tools are acceptable that are designed to process each of the specified surfaces and can be installed on a given equipment, i. e. $\overset{n}{\underset{i=1}{\wedge}}\left(r_{cut}\sim r_{surf_i}\right)\wedge\left(r_{cut}\sim r_{me}\right)$. Denoting the set of solutions r_{cut} admissible for a given transition as $\Omega_D^{r_{cut}}$, taking into account that every surface has a certain shape and involves a certain processing method (*pm*) assigned to the equipment (turning, milling, planing, etc.), we obtain

$$\Omega_D^{r_{cut}}=\left\{\forall r_{cut}\in\Omega_P^{r_{cut}}\left|\overset{n}{\underset{i=1}{\wedge}}\left(\theta_f^{r_{surfi}}=\theta_f^{r_{cut}}\right)\wedge\left(\theta_{pm}^{r_{me}}=\theta_{pm}^{r_{cut}}\right)\right.\right\}. \quad (9)$$

Statement 3. In order to ensure that a cutting tool of a given type is mounted on a given equipment, it is acceptable to have an auxiliary tool that can match the cutting tool (*cut*) with a given equipment, i. e. $\left(r_{aux}\sim r_{cut}\right)\wedge\left(r_{aux}\sim r_{me}\right)$. A formal description of the set $\Omega_D^{r_{cut}}$ of solutions r_{aux} that are admissible for the chosen r_{cut} and given r_{me} has the form

$$\Omega_D^{r_{aux}}=\left\{\forall r_{aux}\in\Omega_P^{r_{aux}}\left|\left(\theta_{cs}^{r_{aux}}=\theta_{cs}^{r_{cut}}\right)\wedge\left(\theta_{vco}^{r_{aux}}=\theta_{vco}^{r_{me}}\right)\right.\right\}. \quad (10)$$

Statement 4. The permissible type of the measuring tool is determined by the type of the controlled surface, i. e. r_{meas}~r_{surf}. Denoting by $\Omega_D^{r_{meas}}$ the set of solutions r_{surf} admissible for a given solution r_{surf}, we will have, proceeding from Statement 4

$$\Omega_D^{r_{meas}}=\left\{\forall r_{meas}\in\Omega_P^{r_{meas}}\left|\theta_f^{r_{meas}}=\theta_f^{r_{surf}}\right.\right\}. \quad (11)$$

Formulas (8)–(11) give grounds to conclude the following:

– the input data of the algorithms for determining acceptable alternatives are the elements of the corresponding sets of possible technological solutions;

– no additional reference information is required for the functioning of the algorithms;

– the output data of the algorithms are the elements of the corresponding sets of feasible technological solutions.

Upon completion of the work of the next algorithm for determining a feasible solution, it is most expedient to transfer control to the corresponding algorithm for determining the desired solution. An analysis of formula (6) shows that the sets of possible and admissible solutions r_{me} coincide, and the algorithm that determines the sets $\Omega_D^{r_{me}}=\Omega_P^{r_{me}}$ is at the same time the algorithm for determining the desired solution r_{me}. The dynamic formation of selection criteria makes it possible to put into practice the most important principle of creating computer-aided design systems – the independence of software from the regulatory and reference base and, as a result, ensure high adaptability of the system to changes in the external environment.

Since the set d_3 of characteristics of solutions r_{to} contains one characteristic each – "name of operations", it should be assumed that $\Omega_{r_T}^{r_{to}}=\Omega_D^{r_{to}}$. For other typical technological solutions, taking into account formulas (9)–(11), the relations take place:

$$\Omega_{r_T}^{r_{cut}} = \left\{ \forall r_{cut} \in \Omega_D^{r_{cut}} \left\| \left[\mathop{\wedge}_{i_1=1}^{n} \left(t_{i_1}^{r_{cut}} ht_{i_1}^{r_{surf}} \right) \right] \wedge \left[\mathop{\wedge}_{i_2=1}^{m} \left(t_{i_2}^{r_{cut}} ht_{i_2}^{r_{me}} \right) \right] \right. \right\}; \tag{12}$$

$$\Omega_{r_T}^{r_{aux}} = \left\{ \forall r_{aux} \in \Omega_D^{r_{aux}} \left\| \left[\mathop{\wedge}_{i_1=1}^{n} \left(t_{i_1}^{r_{aux}} ht_{i_1}^{r_{cut}} \right) \right] \wedge \left[\mathop{\wedge}_{i_2=1}^{m} \left(t_{i_2}^{r_{aux}} ht_{i_2}^{r_{me}} \right) \right] \right. \right\}; \tag{13}$$

$$\Omega_{r_T}^{r_{meas}} = \left\{ \forall r_{meas} \in \Omega_D^{r_{meas}} \left| \mathop{\wedge}_{i_1=1}^{n} \left(t_{i_1}^{r_{meas}} ht_{i_1}^{r_{surf}} \right) \right. \right\}. \tag{14}$$

In general, the solution to problem (4) has the form

$$C_{PO3}\left(\Omega_D\right) = \Omega_{r_T} = \Omega_{r_T}^{r_{to}} \bigcup \Omega_{r_T}^{r_{cut}} \bigcup \Omega_{r_T}^{r_{aux}} \bigcup \Omega_{r_T}^{r_{meas}} \bigcup \Omega_{r_T}^{r_{tt}}. \tag{15}$$

Formulas (12)–(14) show that the desired solutions r_{cut}, r_{aux}, r_{meas} are determined based on the analysis of the values of the characteristics of these solutions. Since each of the types of these tools has its own set of characteristics, it is advisable to determine the required technological solutions r_{cut}, r_{aux}, r_{meas} using separate algorithms, the number of which is equal to the number of types of each of the indicated technological solutions.

The input data of the algorithms for determining the desired solutions r_{cut}, r_{aux}, r_{meas} are the values of the dimensional and accuracy characteristics of the processed elements (surfaces) of the part, the values of the dimensional characteristics of the seats for the equipment tool and the sets of characteristics of the desired solutions that belong to the set of feasible solutions. At the same time, the values of the characteristics of particular technological solutions should be stored in the relevant reference books (technical characteristics of equipment, cutting auxiliary and measuring tools). The output data of these algorithms $r_{cut}^{'}, r_{aux}^{'}, r_{meas}^{'}$ are solutions represented by their designations in accordance with regulatory documents.

Algorithms for optimizing the choice of technological solutions and generating data for designing tools

The presence of a certain property α for a specific particular technological solution r_ξ can be expressed using the corresponding predicate E_α. Then the statement "a particular technological solution r_ξ has the property α" will be written as follows:

$$E_\alpha(r_\xi). \tag{16}$$

The presence of property α for a given solution r_ξ, i. e. the "true" value of the predicate $E_\alpha(r_\xi)$ is completely determined by the presence of the corresponding characteristic t_α in the set d_3 of the considered solution r_ξ. But since each characteristic t_α of the set d_3 takes its values from d_4, it makes sense to assume that the property α has a number of values θ_α. For example, one of the characteristics of a particular technological solution r_{surf} (processed surface) is the shape of the surface to be processed t_f. The characteristic t_f determines the property E_f of the solution r_{surf} to have one form or another. Denoting the value of the property α of the solution r_ξ as $\theta_\alpha^{r_\xi}$ and using predicate (16), we can formalize the statement "a particular technological solution r_ξ has the property α, and the value of this property is $\theta_\alpha^{r_\xi}$" as follows:

$$E_\alpha\left(r_\xi\right) \wedge \theta_\alpha^{r_\xi}. \tag{17}$$

Each value d_2 of the name of a particular technological solution (individual or standard) corresponds to one set of characteristics d_3, which determines the specific properties of a particular technological solution. Each characteristic t_i from the set d_3 of characteristics of a particular technological solution r_ξ, by virtue of axiom (17), corresponds to a particular property of the solution r_ξ. The selection function $C_{PO_4}\left(\Omega_{r_T}^{r_\xi}\right)$, i. e. solution of problem (5), for r_ξ can be represented as

$$C_{PO_4}\left(\Omega_{r_T}^{r_\xi}\right) = C_{P_i}\left(\Omega_{r_T}^{r_\xi}\right). \tag{18}$$

Optimization of the choice of the desired technological solutions by the ideal point method, as shown by formula (18), is based on a comparison of the values of particular technological solutions with the given values of the established optimality criteria. Practice shows that in the general case, each type of a typical technological solution corresponds to an individual set of optimality criteria. Therefore, optimization should be carried out for each using separate algorithms for each type of typical technological solutions. At the same time, the values of the characteristics of the found particular technological solutions belonging to the sets Ω_{r_T} are fed to the input of the solution selection optimization algorithms. For the functioning of optimization algorithms, it is required to introduce directories containing the values of optimization criteria into the regulatory and reference base of the system. The output of the algorithms is the final standard technological solutions. At any stage of choosing a particular technological solution for a specific technological transition, one of the following situations may occur:

$$\Omega_P^{r_\xi} = \varnothing; \quad (19)$$

$$\Omega_D^{r_\xi} = \varnothing; \quad (20)$$

$$\Omega_{r_T}^{r_\xi} = \varnothing. \quad (21)$$

The fulfillment of conditions (19) and (20) means that the required type of technological solution r_ξ has not been found at all. The fulfillment of condition (21) means that it was possible to determine the type of technological solution, but a specific value of r_ξ was not found. With error-free initial data of the system and a reliable reference base in these cases, it is necessary to generate data for the design of a special tool [6]. Registration of data for the design of a tool is carried out in the form of an application for design in the absence of a computer-aided design system for technological equipment at the enterprise. In the presense of such a system, it is advisable to arrange the design data in the form of a file and use it as the input file of the specified system. To implement this function, it is necessary to develop an appropriate algorithm that receives control when the marked situations occur. The block diagram of the system of algorithms for the process of synthesis of technological operations based on a combination of individual and standard technological solutions is shown in Fig. 1.

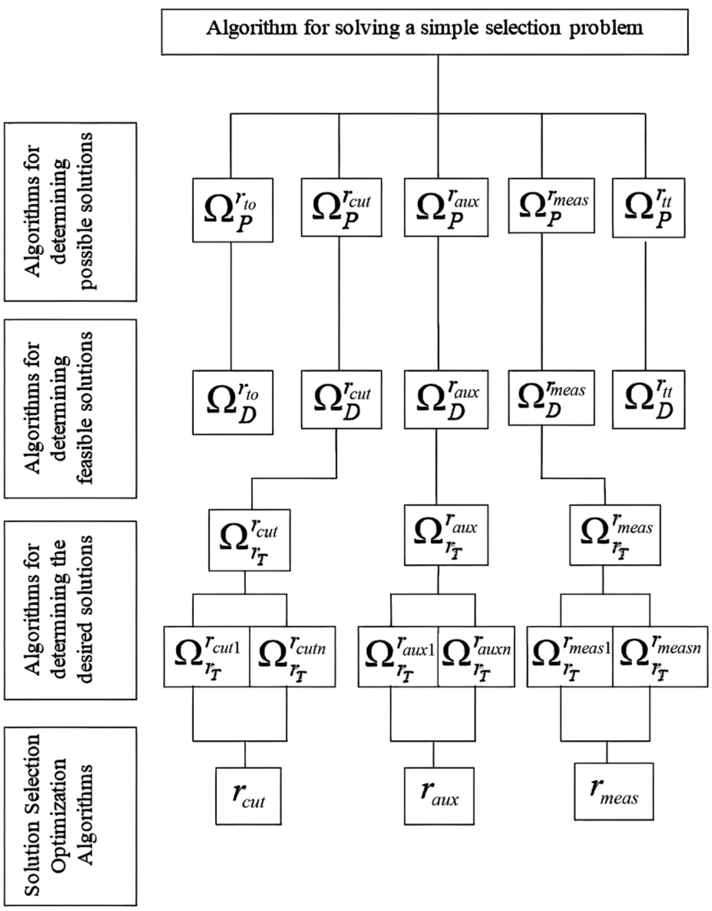

Fig. 1. Block diagram of the system of algorithms

Conclusion

The system has a three-level structure, is characterized by a modular construction, a strict hierarchy of modules. All modules of the system are independent from each other as well as from the reference base of the system. The functionality of the system as a whole is increased by adding new modules to the lower level of the system with a constant core.

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Information about the author

Petukhov A. V., Senior Lecturer at the Department Technology
of Mechanical Engineering of the Sukhoi State Technical University of Gomel

Address for correspondence

246746, Republic of Belarus,
Gomel, Octiabria Ave., 48
Sukhoi State Technical University of Gomel
Tel.: +375 29 734-25-13
E-mail: petukhov_2000@gstu.by
Petukhov Alexander Vladimirovich