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RATIONAL CHOICE OF MACHINE TOOLS FOR DESIGNERS

Monograph

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The monograph deals with the problems of the methodology and toolkit for a rational choice of design solutions, based on the idea of parallel design. The toolkit for embedding the forecast and optimization procedures into the contour process selection is given. A set of postulates that underlie the rationality of the design decisions taken when creating machine tools is formulated. A method of regulating the composition and specificity of information for the effective evaluation of possible alternatives is proposed. The algorithm of interaction of design procedures and operators with criteria that are included in the system of preferences is shown. The application features of the patent and expert search procedures at the initial stages of creating the cutting machine design are considered. A method for constructing a target tree and the corresponding procedures for systematic consideration of development and improvement trends are proposed.

For leading designers, experts in the field of computer-aided design of machines and tools, scientists, lecturers, graduate students and students.
INTRODUCTION

Continuous improvement and development of mechanical engineering is associated with the progress of the machine tool industry. There have been a number of areas associated with increased flexibility, versatility and level of automation. The use of flexible production systems consisting of a set of machines, manipulators, controls, united by a common computer control, makes it possible to move on to new, more perfected samples of products. The transition from the use of machine tools set and other equipment to machine and technological systems (TS), in addition to increasing productivity, radically changes the whole nature of engineering production.

In the total labor intensity of the cost of new products 80 ... 85% falls on the stages of design and technological preparation of production. Rational design involves the ability to continuously improve the performance of machines and reasonably combine unified and promising solutions. The fundamental research in this area was carried out by scientists V.V. Bushuev, K.D. Zhuk, Yu.N. Kuznetsov, A.P. Gavrisch, S.V. Yemelyanov, A.A. Timchenko, V.A. Dechtyarenko, Yu.M. Solomentsev, A.F. Prokhorov, L.A. Kuznetsov, G.L. Khmelovsky and others. Design problems associated with multi-iteration, recurrent nature, multi-criteria gave impetus to the idea of “parallel construction” as an alternative to the set of consecutive acts of making design decisions”.

The peculiarity of the design process is the “permanent” undeterminedness of the source data and the limitations of the design procedures under consideration. The need for additional definition makes the task of TS constructing makes a search, related to the problem of reliable prediction of design solutions. Currently, TS
developers do not properly use the most progressive principles of operation for technical objects and systems, new design solutions, limiting themselves in their activities to the compilation of best practices of organizations. As a result, many existing developments can be considered no more than emergency measures and means to “dampen” the stream of innovations.

Multivariate design of complex TS is associated with the achievement of high accuracy, performance, rigidity and other output indicators. At the same time, decision making is optimization.

There are many methods and tools for optimizing engineering solutions. Geometric programming methods developed by C. Zener, R. Duffin and J. Wilde are attracting more and more interest. The advantage of this method is an effective assessment of the comparative significance of various project parameters, adaptability to computer-based computer processing methods and, importantly, a close relationship with the engineering essence of the tasks.

The need to create a single integrated procedure for the rational choice of design decisions predetermined the task of this monograph - the development of methodological and experimental bases for the rational choice of the best design options for technological machining systems, including:

- building a model and toolkit of choice based on parallel design;
- development of methods and algorithms for forecasting the development of TS components;
- formation of optimization models using a complex of algorithms and programs.

The monograph proposed a new formalized rational choice apparatus, the necessary components of which are parallel implemented tasks of prognostic analysis and optimization. A detailed toolkit developed for the interaction of the selection scheme individual components. A description of the declarative and procedural model providing together with the system of priorities the rational choice procedure is given.
The monograph presents the experimental aspects of optimization and rational selection of the spindle assembly structures on rolling bearings. As an analogue, a four-coordinate specialized drilling-milling-boring machine model SF68VF4 was used. Various schemes of two-bearing structures, variants of connections and mounting of bearings, their lubrication and sealing are considered.
1. ANALYSIS OF DESIGNING PROBLEM FOR TECHNOLOGICAL SYSTEMS

1.1. System approach to design

A systematic approach to the design of technological systems (TS) [1, 2, 3] underlies the modern methodology for creating machine tools, software for controlling their operation and tooling.

In the conditions of mechanical production, technological processes interrelate, forming objects of a higher hierarchical level – the system of technological processes. The systemically important parameter for technological systems is a new function. It is the impossibility of performing the required function by individual elements (technological processes) that makes them combine into technological systems. There are no technological processes in the production system that function independently of others. All technological processes are combined in systems of different levels. It is obvious that through communication channels there is a mutual influence both on the part of the technological process on the state and level of the technological system development, and on its part on the level of the technological process development.

Under the technological system (TS), according to GOST 27.004-85, understand the set of functionally interrelated means of technological equipment, product of machinery and performers to realize in a regulated production conditions specified technological processes or operations.

Modern TS are complex technical systems, including a set of mechanical, electronic, hydraulic and pneumatic elements, united by one purpose: “Manufacturing of end products of labor (parts, assemblies)
with given requirements to the quality and accuracy of their components”.

The main features of a systematic approach to the TS design are:

- complex consideration of various factors, identification of the relationship and the role of an object part, as well as the requirements for it. The object being consideration from various points of view. Consideration of geometric and kinematic features gives an idea of the theoretically correct forms of parts, of their movements in the absence of conditional forces. An energy perspective provides information about the cutting forces components, points of application, lines of action and the results of action;

- multivariance inherent in any kind of design activity. Each option is considered on the basis of the requirements of the task, taking into account various criteria of efficiency;

- recurrent in nature, when layout and schematics decisions made at the initial stages of TS design (technical proposal) may vary depending on design decisions made at subsequent stages (draft and technical projects). On this basis, a cyclic design strategy is built [1], characterized by the presence of feedback, including in the form of several feedback loops covering each other;

- multi-criteria inherent to complex and multifunctional systems, which are the TS. Today, the design situation is not uncommon, when the assessment and selection of the variant (s) is carried out on the basis of 10 or more specific criteria [4];

- optimization of decision-making, which, in the presence of a vectorial quality criterion, consists in choosing a compromise option based on the resolution of contradictions. The paper [5] presents the mechanisms of optimal design effectively used in modern technology and technology;

- predictive nature of the project procedure. Continuous improvement of the TS and its components, access to competitive options makes it necessary to better use the arrays of patent data, expert assessments, time series, changes in the main characteristics studied. In
this regard, it is also necessary to take into account the fundamentally uncertainty of the project procedure, which can be reduced by entering a prediction contour, which determines the initial data and limits the sought-for procedure.

The traditional consideration of the design process as a sequence of acts of analysis, synthesis and decision-making fraught with a number of contradictions. They are laid in the itself basis - a consistent analysis of the TS elements, the subsequent synthesis of many options and the choice of the desired one. Consider as an example the process of designing instrumental adjustments on machine tools.

For the first time, this problem was set a task and propose its solution by G.I. Temchin [6]. This task is considered as a variant technical and economic problem, i.e. the task of choosing the most cost-effective combination of a structural variables set and process parameters, taking into account existing relationships, technical limitations and other dependencies. The complexity of the formulation of such a task is a consequence of the presence of a subtasks set, including the definition:

- the number and workpiece method of location on the machine;
- order manufacturing step with sequential and parallel processing;
- intertitle allowances and tolerances;
- type of tools and tool materials grade;
- number and size of tools;
- geometrical parameters of the tool cutting parts;
- cutting conditions associated with the technological capabilities of the machine and organizational-production conditions.

There are several approaches to solving this rather complex task. The first is related to its reduction to the problem of mathematical programming [6]. In the absence of analytical dependencies, the use of a random search type procedure is allowed. The second is associated with the use of structural optimization (along with parametric) [7]. The structural optimization mechanism is presented as an iterative one, including:
- making a decision on the improvement of the reference option (using the results of the cutting mode analysis obtained as a result of parametric optimization of the previous admissible adjustment option);
- repeating the improvement process for each of the next admissible adjustment options;
- making a subjective decision about the design ending (personal point of the designer view predetermines the end of the iterative process of improving the adjustment structure).

The third method is focused on converting a task to a two-stage non-optimizing procedure for the feasibility of a technological operation (drilling, core drilling, reaming and threading) and selection auxiliary and cutting tool [8]. Such a transformation is feasible only if the task is simplified by limiting the type of equipment (aggregate machines and automatic lines).

An analysis of the choice logic inherent in these three approach shows that they are embedded in the traditional scheme for the implementation of this process. Imagine the task of designing instrumental adjustment in the form of the following scheme (figure 1.1).

The main difference introduced by the authors in the traditional scheme of choice consists in the formation particular of the initial set of alternatives. This procedure is implemented as a result of a step-by-step improvement of a certain $i$-th initial version using the parametric optimization data for this variant.

The main techniques for improving the $i$-th adjustment option are:
- increase the feed of non-loaded tools adjustment due to the redistribution of the load on the adjustment tools and the introduction of additional tools;
- replacement of the cutting part material for the limiting tool (by durability);
- input to the operation structure of fast-working (in particular, fast-drilling) retaining devices.
Along with the peculiarities of the formation basic set for design alternatives in the mechanism for implementing the design process, there are a number of problems. One of them is the problem of pick and allocation of essential preferences that predetermine the choice of criterias (criterion) for decision-making.

In order to answer the question of choosing the preferences of the designer, it is necessary to first solve another choice problem, as a result of which the necessary criterias are selected [9, 10, 11].

The next problem seems to be nested in the previous one and is formulated as follows: exactly what information is needed in the task of choosing preferences? The answer to this question can be given by researching the properties of the alternatives themselves (instrumental adjustment options).
In the general case, the set of properties characterizing the adjustment and influencing the selection process is constructively large. These include:
- design details data: the size and weight of the details, the accuracy and roughness of the machined surface, the material grade and the delivery condition;
- information about the organizational indicators of production (batch size, program of release, form of work organization), etc.

An attempt to limit the task by taking into account only the essential (important) properties comes up against the question: what preferences are we going to use? But the choice of these preferences is based on the analysis of selected properties.

The given example, which leads to a type of closed-loop contradiction, is characteristic of the procedures of analysis, synthesis, and decision making when creating new TS structures.

1.2. Problems of optimization of design and technological solutions

Designers of modern technological systems having imagined the designed object as a whole should then carry out the development or selection of its elements based on considerations of economy and reliability. For an experienced developer, it is typical to make rational (possibly the best decisions) already at the stage of a draft design. However, the designer's intuition is due to the use of certain design principles. And since the main share of the information contained in the drawings of engineering structures is presented in accordance with the laws of geometry and is numerical information. Designer find a rational design solution, which is either the best of all acceptable solutions (optimal design solution, optimum), or very close to that (quasioptimal). Currently, there are a number of works devoted to the optimal design in
the field of machine tools. In a separate section, works on MultiCriteria (vector) Optimization (MCO) are highlighted.

The analysis of works devoted to MCO of the machine tools design and its main components shows the presence of three main approaches:

1. The most traditional, associated with the introduction of the generalized criterion [12, 13, 14]. In [12], the generalized criterion $Q$, presented in the form of a linear convolution of two criteria ($i = 1, 2$)

$$Q = \min \sum \lambda_i \frac{F_i - F_{inw}}{F_{nb} - F_{nw}},$$

where $F_1, F_2$ – the non-circularity of the hole being machined and the maximum displacement, respectively;

$\lambda_i$ – weights coefficient;

$nb$ and $nw$ are the best and worst values of $F$.

A similar approach is used in [13], dedicated to the optimization of the criteria of the carrier system (CS) of rotary machines. It also uses linear convolution on the criteria:

$F_1$ – the mass of the carrier system;

$F_2$ – CS stiffness.

One of the most difficult, non-formalized questions is the determination of weights $\lambda_i$. The authors of [14, 15] proposed a rather efficient method based not on experimental evaluations, but on the experience of creating the best prototype samples of the considered class of machine tools. If the values $\lambda$ of two of these prototypes are stable (we can talk about the balance of the distribution $\lambda$ or their relationship), then such $\lambda$ can be used as a first approximation as a weight.

Optimization of the spindle node dimensions (diameter ($d$), inter-reference distance ($l$)) using an additive (linear) generalized criterion is considered in [14]. The stiffness and temperature of the supports is considered as particular criteria. It is proposed to determine the weight coefficients taking into account the stable position of the compromise
solutions line in the plane of optimized variables “l – d”. It is characteristic that the stability of the position of this line (shift up to 20%) is preserved even when the criteria are changed (spindle beating, bearing durability, dynamic rigidity).

2. The second approach is based on the mandatory selection and study of the Pareto-optimal region of non-dominated points. In [15], using the characteristics of load-carrying capacity, accuracy, maximum speed of movement of the machine robot arm, Pareto-optimal area in the space of indicators, which is approximated by the surface \( F(x) = C \) is built. For each the estimated sample calculates its deviation from the approximated surface and estimates the allowable value of the compromise.

In the task of optimizing the spindle design of a metal cutting machine (MCM), two particular criteria are used [16]: the total weight of the spindle and the bending compliance (or torsional compliance), which form the functional space of the two criteria in which the Pareto region is built, and therefore fixed Pareto optimal design solutions set. To determine the weight factors, the authors use a generalized criterion in the form of a linear normalized convolution (relative to maximum values of compliance and weight), introduce Lagrangian and vary with different combinations of active constraints (using Lagrange multipliers). The paper discusses options for smooth and stepped shafts with two and three optimization criteria - the criterion “Main natural frequency of torsional vibrations” is added to the weight and flexibility of the spindle. External and internal spindle diameter are considered as optimized variables, which predetermines consideration of curves (and not surfaces) on which Pareto-optimal points are located.

A similar approach is also considered in [16], where Pareto-optimal design solutions are built using the example of the milling machines design. The concepts of a power contour that closes at the point of cutting and includes: upright, traverse, reduction gearboxes (gearboxes, engines) and couplings are introduced. The following are considered optimal variables: a) design characteristics of the power circuit elements with a
rectangular cross section; b) the design characteristics of the structural elements and connections outside this contour, and finally, the damping coefficients characterizing all the connections of the milling machine.

The following optimization criteria are used: a) the total weight of the structural components on the power circuit; b) static compliance; C) the maximum value of the real characteristics of the transfer function. In order to reduce the complexity of the search, it was proposed to carry out a preliminary refinement (agreement) between conflicting and non-conflicting relations on optimized characteristics.

The complexity of modern machine tool systems (MTS) determines the need to enter into consideration a large number of performance criteria. Today it is not uncommon to score on 10 or more criteria. In this case, the approach associated with the use of two- and three-dimensional graphical modeling on the Pareto-optimal set of non-dominated points becomes unacceptable.

3. The third way to solve the MCO MCS problem is to use the LP-search apparatus [4, 17, 18]. There is an interpretation of attributing it to the simplest methods of approximate construction of the Pareto set. Today, more than a dozen works in the field of designing machines using this method are known. So in [19] a five-criteria four-parameter optimization problem designs of internal grinding heads was formulation. The search is carried out in 32 test points, which does not always guarantee the achievement of a correct result. How to choose the number of points and associate this choice with acceptable accuracy is not specified in this work. The second problem is connected with the completeness of the criterial space. As well as with the criteria of compliance and reduced load on the front support, the introduction of three criteria for minimizing the radius-vector of Amplitude Phase-Frequency Characteristics (AP-FC) at the first three natural frequencies more characterizes a particular case of the functioning of the internal grinding head.

The methods of LP-search is used to optimize the spindle assembly (the elastic system “spindle-support-housing”) in [20], where the problem
of finding a compromise of the spindle assembly variant by the accuracy criteria (6 criteria related to dimensional accuracy, shape and surface roughness) and the criterion of dynamic quality (oscillation amplitudes in resonant zones). is solved. At 1024 points, the space of varying design parameters was uniformly probed (relative outreach and inter-support distance, dynamic viscosity of the lubricating fluid, and pressure of the power source). Using the proposed technique, several optimal variants with reduced values of the Amplitude Phase-Frequency Characteristic radius-vectors and an increase in the output accuracy of the machine as a whole were found.

The optimization of the design and geometrical parameters of the cutting part of the shaped cutter is described in [21]. Based on the criteria: machining cost of profile accuracy and roughness of the treated surface, LP-search was performed [22-24]. Based either the dominant cost criterion or the normalized linear convolution of the criteria, without recommendations for assignment (calculation) of weights was select the best option. The paper [25] also points to the connection of the Pareto-optimal and LP-search methods.

The optimization of machine components by the criteria of dynamic quality (static and dynamic stiffness, vibration resistance, nature of transient processes) was carried out at a set of effective points in the Pareto-optimal region, and the formation of such a set is carried out using $LP-\tau$ sequences.

Optimization procedures in the CRDS2 [19], VIMOS [20, 21] application software packages are increasingly included. The VIMOS system the problem of optimizing the layout [23, 26, 27] and the carrier system of machine tools are solved [28]. According to the criteria of dynamic and static compliance, as well as the pressure in the machine slideways are searched for optimal parameters of the carrying system of lathes. Such a search taking into account dimensions of the front and rear parts of the machine slideways, as well as the weight of the spindle head at 1024 test points was carried. The feature of this task “$3 \times 7 \times 1024$” is transition from one set of optimized variables to another based on
optimization results, changing the set of optimality criteria depending on the purpose of the designed machine. As well as additional analysis of the Pareto-optimal set of solutions and identifying the main development trends also a feature of this task.

Another means of enhancing the effectiveness of MCO is the use of an expert system [26], which is by dint of to pre-select alternative layouts and their comparative evaluation by non-formalizable parameters. In the same work, a set of six performance criteria (static and dynamic compliance in axial and normal direction, material intensity and the minimum real component of AP-FC is formed. Along with the expert system, this work also uses the software package for analyzing the balance of the kinetic and potential vibrational energy. It is on the basis of the calculated balance that the dominant elements (upright, slideway) are selected according to the maximum dynamic compliance and, therefore, optimization parameters (masses of moving parts, dimensions of slideway, etc.) [29-31].

When solving technological problems associated with the MCO of the cutting process on metal-cutting machine tools, as a rule, the same transitions are used as in solving design problems.

1. Using convolution of private criteria efficiency. As a rule, this criterion is technological cost, productivity and profit. Thus, in [32], a two-criterion (time per piece $t_{pp}$ and unit cost $C_u$) three-parameter problem (speed $V$, feed $f$ and depth of cut $d_c$) was solved with the help of normalized linear convolution with weights. Behavior analysis of compromise criterion ensures the achievement of optimal values of $V$ and $f$ as a result of determining either the point of tangency of the objective function with one of the constraints, or the point of intersection of the constraints [33-35]. This uses a re-selection procedure with initial feed values in the right-hand area of technical constraints. For a three-parameter problem, the algorithm is tuned to search for optimum $d_{co}$ with fixed values of $V$ and $f$, and then the search for the minimum of the estimated function $F(V, s, d_{co})$ is found.
2. The use of characteristic functions [36, 37], including Pareto-optimal solutions in the case of consideration of two particular criteria: cutting intensity \( R = V \cdot s \) and tool life

\[
T = \alpha_0 \cdot s^{\alpha_0 + \alpha_1 \ln s}
\]

2. The characteristic function “R-T-F” [37] provides a search for extra min (max) distance to the vertices of the feasible solutions polygon, formed by restrictions on the elements of cutting modes (D).

If the “R-T-F” curve intersects the range of admissible modes, then the problem reduces to optimizing the optimality criterion (for example, unit cost) in the intersection region of “R-T-F” \( \cap \) D.

3. Replacing several partial criteria with one of the most important ones [38-41]. The choice of the dominant criterion is based on the analysis of the production situation:
- if the machine limits the output, the processing performance bring to front;
- if the machine does not limit output, then the unit cost criterion dominates;
- if the machine is underloaded, then the costs associated with the tool become a decisive.

Optimization of individual criteria is complemented by comparing the results obtained by these criteria [42, 43]. It is generally accepted to design solutions that are between the optimal values of cutting conditions for criterion unit cost and productivity criterion. In [42], a trial algorithm for “probing” these points was given by distinguishing the ranges of mode changes and evaluating their influence on the values of particular criteria.

4. Using the LP-search method to select the working conditions and design efficiency of step mills [44]. The authors search for optimal values of \( V \) and \( f \) according to six criteria of effectiveness (durability, temperature, roughness, etc.). Decision making is related to the analysis
of the test table and the limitation of the number of criteria (the transformation of a 6-criterion task into a 4-criterion task).

The LP-τ sequences \((N = 20 \text{ points})\) are used to identify the two-parameter tool life dependence \(T = f(V, s)\) that has extremes at different feed values of \(s\) [45].

The analysis of the above problems of TS designing allows to formulate a number of theses and provisions, without the resolution of which further progress in this direction is impossible.

1. The problem situation associated with the use of the methodology and, especially, of the system analysis toolkit in the problems of TS designing [46-48]. The thesis about the need to transition from the structures calculation, functional diagrams and the release of drawings to the programming of life cycles of a whole generation of new equipment and the definition of consequences [49] has not yet found a constructive implementation in the processes of TS designing.

2. The complexity and labor intensity of the TS design process is caused by a recurring nature and a large number of iterations, which are predetermined by the absence of integral TS models covering all stages of the life cycle (design, manufacture, exploitation) and the simulation procedure for the consequences of introducing the production facility into the environment of exploitation and manufacturing.

3. The problem of multivariance and the allocation of rational options is not effectively resolved due to the absence of clear recommendations for assessing the quality of the generated design decisions at each stage and the allocation of “threshold” values by which a subset of rational options is formed.

4. There are problems like “completed circuit” in the design mechanism itself:

a) extraction and selection of essential preferences when choosing a project option;
b) determining the information that is needed in the task of choosing preferences;
c) selection of those properties of design alternatives, on the basis of which information is selected for the choice of preferences.

There are no clear recommendations for resolving this kind of completed cycles in the TS practical design, which leads to the emergence of procedures such as “trial and error”, an systemless step-by-step improvement of the basic variant, etc.

5. Modern TS design systems should be ready for a permanent change of design objects (TS) and the ability to adequately develop the functional components and toolkit of the system as a whole. It is possible to ensure such development subject to the availability of a timely, advanced system for tracking trends and forecasting the objects under study. Neither large machine-tool enterprises, nor industrial design institutes do not use such forecasting systems.

To select the TS optimal variant, it is necessary to solve a multi-criteria optimization problem. Despite the significant number of MCO methods and examples of solved problems, the systematic methodology and toolkit for applying various MCO methods have not been proposed. Such a toolkit should be aimed at express-analysis of the problem itself, the formation of the MCO model, the choice of optimization method(s) and the assessment of the quality for the designed project solution.

In connection with the foregoing, the task of the research of this monograph is the development and study of the methodology and toolkit of rational choice.

To solve the problem in the monograph it is proposed to perform:

1. Develop a methodology and toolkit for a rational choice of project TS options.

2. Generate a set of optimization models for TS components in a multi-criteria formulation.

3. Implement the toolkit of rational choice and multi-criteria optimization in the practice of TS designing.
2. METHODOLOGY AND TOOLKIT OF RATIONAL CHOICE FOR TECHNOLOGICAL SYSTEM VARIANTS

2.1. Main project procedures and their description

The process of designing complex technological systems (TS) cannot be reduced to a simple choice between several alternatives according to one (or at most several) alternative by performance criteria. Such a complex object must be adequate in complexity and design procedure. The improved logic of choice of alternatives [9], gives the main reference points for finding new approaches to design, while remaining only part of this procedure. Other components of analysis and synthesis remain unrevealed parts of this process.

Consider a rational choice scheme in relation to the problem of designing technological systems [9]. The need to clarify the initial logic of choice (Fig. 2.1) is caused by the difficulties in answering the question: how is the selection of project preferences in a given choice situation? And hence the question: what information comes in block Evaluation and Alternative Comparison (figure 2.1.)? In different production situations in the presence of different batches of machined parts, various operating conditions of the equipment (production line, CNC department, flexible production system), the designer can use different ideas about the purpose of choice. So in the conditions of the production line, when the productivity or the production cycle is given, the unit cost of the machining comes to the fore. In terms of pilot and individual production, priority considerations related to maximum productivity are possible.
When taking into account several criteria of optimality the best version of the TS will be a compromise. Moreover, at various stages of the design process (processing scheme, layout, etc.) additional partial selection criteria are introduced.

In order to answer the question of choosing alternatives, the designer essentially solves another choice problem, the result of which is the extraction of the necessary selection criteria [50-52]. Thus, the initial logic is transformed into a modified selection scheme presented in figure 2.2.

A variety of production situations leads to a large number of alternative preferences and differences in priorities placed by the designer on this set.
Further analysis of the scheme (figure 2.2) leads to a problem situation related to the answer on question: what kind of information is needed in the task of choosing preferences? The answer to this question can be given by studying the properties of the alternatives themselves (TS variants).

Fig. 2.2. Modified scheme of TS selection
(First modification step)

In general, the set of properties that characterize the TS and affect the selection process is "constructively large." These include:
- properties inherent in the cutting machine tool, as the most expensive and complex component of the TS and including achievable accuracy, rigidity, dynamic stability, productivity and other technological capabilities;
- properties inherent in the cutting tool, in terms of its design, geometry, material of the cutting part, the presence of coatings;
- properties of workpieces, including the accuracy of shape and stability of the materials properties (uneven distribution of hardness, technological defects in the material, etc.);
- environmental properties associated with temperature stability, the level of dust in the atmosphere, humidity;
- properties of working processes (cutting, friction), which change the initial state of the TS in terms of processing accuracy and dynamic state of the system itself.

An attempt to limit the task by taking into account only the essential properties comes up against the question: what preferences are we going to use? After all, the choice of these preferences is based on the analysis of selected properties. The only way out of the completed circle is the rejection of the implicit assumption of both the independence and the hierarchy dependence of the two components of choice [9]:
1) represent about the TS variants;
2) represent about the preferences of the designer.

In this case, the process of selecting project alternatives (TS variants) is not limited to the assessment and comparison of the available options, but consists in the simultaneous (parallel) construction of the two above-mentioned components. And the resolution of the contradiction: "preferences - properties of alternatives" will practically be connected with the introduction of a new aspect - an represent of actions, i.e. with represents about what exactly we are selecting this or that alternative, how we are going to use it. This aspect is associated with the so-called procedural knowledge [54]. In contrast to the latter, the full description, general provisions concerning project alternatives in general, are called declarative [54]. The difficulty facing the designer will be that having a full description of alternatives, distinguish between information (facts) that should change as a result of actions (processing type, shape of detail, mounting method) from information that remains unchanged as a result of this action.
The peculiarity of this consideration is that the represent of alternatives, actions and preferences appear here not as independent inputs, but as the same artificial objects as the result of the choice itself. The fundamental importance here is the fact that the construction of four source objects:
1. The set of alternatives considered;
2. The represent of alternatives (declarative knowledge);
3. The represent of actions (procedural knowledge);
4. The represent of priorities,
and one target object, the “result of the choice,” is carried out in parallel, rather than sequentially, and the choice of any of them is equally explained by the choice of the others.

Graphically, such a "completed" logic of choice can be represented on the example of the object “Spindle Unit (SU)” as a TS component (figure 2.3).

![Diagram of Spindle Unit selection process](image)

Fig. 2.3. Modified scheme of Spindle Unit selection (Second modification step)
With the multivariate design of complex SU, it is very laborious, and often impractical, to fully develop all possible options [55, 56]. The selection of a subset of feasible options is carried out at almost every stage of the machine design (layout, design and (or) calculation scheme, preliminary design work). Therefore it is important that the separation representations on the variable and unchangeable parts, including a complete description of the SU variants is carried out for those alternatives that have passed through the "scheme-type riddle".

When constructing objects of the selection scheme (figure 2.3), the designer has to deal with a different level of detail in the presentation of information. So for the object "Variants of the SU" the integrated level of description is typical in the form:

1) structural kinematic schemes, which are a combination of kinematic groups (source of motion, executive part, adjustment parts and kinematic relations) [57];
2) the layout of the technological equipment for the TS, which is a set of nodes and assemblies, characterized by the type and nature of the spatial – power interaction [58].

In addition, when using innovations in the design process and the absence of prototypes of the designed structure, it is necessary to choose the principle of operation, i.e. to determine the general technical idea of the device, including the choice of the type of movements, the method of basing, the source of movement, etc. Another type of enlarged description is the development of a constructive solution without scale (a sketch of structural elements by hand and (or) on a computer).

The second object of the selection scheme is a set of drawings, technological processes (a set of sign models in a computer database), designed in accordance with ESKD, ESTD and other GOSTs. These are drawings of parts, assemblies, assemblies and the TS as a whole, as well as transformation operators (design operations, calculation procedures) of the components into the overall design of the TS. Thus, a declarative representation is a complete description of the TS design and working processes, including the synthesis operators of complex design solutions.
The third object of the selection scheme is detailed fragmentary data related to the main most developing components of the TS (main components and parts of the machine, the design of the tool cutting part, etc.). A feature of the procedural presentation is a immediate direct connection with the main goals of improving the TS. If we consider as an example the design of a spindle node for the TS, then the procedural data database stores options for implementing increased accuracy (data related to the system of preferences), such as reducing the size of cantilever, options for implementing preload on the front and rear supports). Moreover, this information is initiated by target information (from the system of preferences). The fourth object of the selection scheme should contain all performance criteria, allowing to evaluate the usefulness of the presence or absence of any alternative property contained in the declarative model of alternatives.

2.2. Basic postulates of rational choice

The coordination of the scheme’s object (Fig. 2.3) is carried out in accordance with the principles of mutual completeness and internal consistency [9, 59]. Interpretation of the first of them can be interpreted as follows. The procedural concept of alternatives must contain all actions to modernize those parameters of declarative knowledge, for which instead of real information the theoretical information are used. All these actions necessary to make the transition from the initial design state to the final state are used. These transformative actions are associated with a sequence of operators in heuristic search problems, the formulation of which can be describe and formalize as follows.

Set: 1) the initial situation – the components of the TS (parts and nodes of the machine, tool, retaining device, kinematic layout, components of work processes, including the route, the sequence of manufacturing step, modes, etc.);
2) a set of operators that transform one design state to another;
3) final or target situation.

It is required to find such a sequence of operators that transforms the initial situation into the final one, is optimal in a certain sense and provides the choice of the TS optimal variant.

Such a procedure can be formalized as a quadruple [60]:

\[ \{S_0, S, F, T\} \]

where \( S_0 \) is the set of initial design states, \( S_0 \leq S \);

\( S \) - set of states;

\( T \) – set of final states, \( T \leq S \);

\( F \) – set of operators, \( P = \{f\} \).

Each operator \( f \in F \) is a function that reflects \( S_f \) to \( S \), where \( S_f \leq S \) – the domain of definition of \( f \); if \( S_f \leq S \), then the operator is applicable to the set of states \( S \).

The solution of the problem is such a sequence of operators.

\[ f_1, f_2, \ldots, f_n \ (f_i \in F); \]

\[ f_1 \circ f_2 \circ \ldots \circ (f_n(S) \in T), \]

where \( f_1 \circ f_2 \circ \ldots \circ (f_n(S)) \) – composition of the function: \( f_n(\ldots f_2(f_1(S), S \in S_0, \) and this composition is determined if \( S \in S_f, f_i(S) \in S_{f_d}, \ldots f_n(f_2(f_1(S))) \in S_{f_{n-1}} \).

The method of solving the problem \( \{S_0, S, F, T\} \) is similar to the heuristic search method, when at each step the procedure of applying (all possible applications) of operators to this current state is implemented, and the order of operators application of is controlled by the properties of the state steps already considered before.

The principle of internal consistency is associated with the well-known strategy of “Test Thinking”, when a design decision is made immediately (based on experience, intuition), and thinking time is used.
mainly manner to substantiate the correctness of the chosen solution. This strategy is to extend such minimal represents about alternatives, preferences, and actions that will not change the choice results. In addition, the principle of internal consistency regulates the relationship of the three source objects of choice (declarative and procedural model and system of preferences) with the resulting object (“Optimum variant SU”, figure 2.3). It consists in this construction the above three source objects so that the chosen design alternative is optimal (by singular criterion) or quasi-optimal (best compromise) by vector efficiency criterion (from “Preferences System”, figure 2.3).

To justify the rationality of choice the above interpretation of the mutual completeness principle is not enough. In view of [9], we formulate a set of postulates, the fulfillment of which will make it possible to judge rationality.

Postulate 1. The “Declarative Model” (figure 2.3) should contain information sufficient for the implementation of the project operators contained in the “Procedural Model”, taking into account the description of the actions consequences for these operators.

Postulate 2. The “Declarative Model” should contain all the information necessary to evaluate alternatives according to the criteria included in the system of preferences.

Postulate 3. The “System of Preferences” (figure 2.3) should contain all the criteria that allow to evaluate the effectiveness of the designed structure, at the level of the Declarative Model.

Postulate 4. In the “Procedural Model” (figure 2.3) all actions must be carried out, thus allowing the TS design to be upgraded so that any of the efficiency criteria belonging to the System of Preferences can be applied.

Postulate 5. The “System of Preferences” should include all performance criteria that allow to evaluate any modifications of the original structure presented in the Procedural Model.
Along with the above discussed basic principles of mutual completeness and internal consistency, a rational choice scheme should be formed on the basis of two more principles:

a) the minimum dimension of the description;
b) generally accepted significance.

The first of these is predetermined by the mechanism for introducing the rational choice model itself, the problem of reducing the design properties and parameters of design alternatives. This principle can be formulated as follows:

"The result of the construction of three source objects of the choice scheme should be minimal, i.e. discarding any component violates either the internal completeness of the description or the internal consistency of choice".

The principle of generally accepted significance reflects the fact: the choice result includes all those components that are considered necessary (rational) within the confines of the discipline to which the projected system belongs.

Thus, if the aforementioned technology of TS parallel construction corresponds to the four principles and the main postulates listed above, then it can be argued about a rational (optimal) version of the TS designed.

2.3. Script rational choice of TS

The process of parallel construction of the TS in accordance with the basic postulates will be carried out be following scripted:

1. Taking into account the project requirements, a number of initial options are extracted from classifiers of structural kinematic schemes and TS layouts that implement the technological process of manufacturing a given workpiece spectrum. For the absence of known arrangement layout solutions, in case of impossibility to implement the requirements of the project requirements by existing means, it becomes necessary to search
for new principles of action, new materials, etc. From this set, on the basis of the criteria of limiting states, the selection of admissible variants arriving at the input of the object “Declarative Model” is performed.

2. Further design associated with the formation of a drawings set for each of the selected layout options. Moreover, a feature of this stage is the use of declarative (complete, theoretical) representations. There are associations with the method of construction on the "mole rat". Each layout, in general, has several declarative type implementations.

3. Provision of target installations is carried out by docking of TS declarative and procedural models. The designer should be able to select the minimum necessary subset of facts (details, fragments) relevant to the current stage of solving problems. This ensures that there are procedural represents. As an example, consider the design situation associated with the target installation: "Increased durability". Such a setting relating to the object "Preferences System" highlights a fragment of the procedural model associated with the cutting tool. In this fragment, data is extracted (from working and reference files) regarding promising cutting materials (cermets, cubic boron nitride and other superhard alloys), which, under given conditions, are characterized by increased durability. In this case, on the one hand, quantitative estimates are used that determine the exact (averaged) values of tool durability, on the other hand, tabular data identifying the calculated dependencies. In addition, the same section presents progressive versions (using patent and expert data) of the construction fragments: cutting plate fasteners, chip breaking devices and options cooling. Formed options advanced cutting tools are fed to the input of the TS Declarative (full) Model.

4. Docking of declarative and procedural representations is carried out by replacing the original version of the TS element (in the example it is a cutting tool) with an improved fragment, joining it with other TS fragments with subsequent design and verification calculations. Such calculations include calculations for the tool holder and the cutting plate by criterion of strength, calculations for the possibility of providing the specified cutting conditions for a fixed period of durability, etc.
5. A change in fragments of the “Declarative Model” can be accompanied by a simultaneous change in the object: “System of Preferences”, consisting in switching to a new design model of durability and a possible change in the efficiency criterion along the following chain: unit cost → time per piece → cut machining time.

6. For docking of declarative and procedural representations in this script, it is necessary to develop appropriate toolkit. Consider the means necessary to update the objects of the choice scheme.

2.4. Toolkit rational choice of TS

In order to bring the modified TS choice scheme (figure 2.2) to the design practice and implement the script proposed above, it is necessary to develop appropriate toolkit. Consider the means necessary to actualization the objects of the choice scheme.

2.4.1. Toolkit object "TS Options"

Primary enlarged versions of the TS are formed on the basis of the main “Project Requirements” (PR) document for the design and the carried out design examination of the existing prototypes, the workpiece spectrum and their manufacturing technology (at the level of routing technological processes, RTP). The most appropriate way to examine prototypes is to use known variants of the implementation of kinematic schemes and layouts, often presented in the form of classifiers. However, already at the first stages of TS designing, which, as a rule, are carried out by the lead designer, it is not enough just known solutions. A patent and expert search for new design solutions in terms of physical effects and operating principles that implement the overall technical scheme of the device is required. As soon as the contours of the future TS begin to emerge, the chief designer selects the design team and distributes the entire range of works. Depending on the adopted set of initial options, the
composition of the specialists for the selected project unit may change (for example, there is a need for an adaptive management specialist, or a technologist for composite materials, etc.). This characterizes the appearance of feedback in the fragment of the toolkit scheme for the object “TS options” (figure 2.4).

In this diagram (figure 2.4) all tools are represented as blocks in a double frame. They also provide the implementation of the first stage of TS designing in the form of a set of possible variants of kinematic schemes and layouts. Already at this stage, a primary analysis is made, discarding unacceptable (taking into account PR and RTP) options and choosing the best. This choice may not be final and may be changed depending on the results obtained in the subsequent stages of the TS design.
2.4.2. Toolkit object "Declarative model of the TS"

As noted above, the declarative presentation of information about the TS is a complete, workable representing of the design object. When forming such a presentation, a set of parts and assembly drawings for the TS, master of route and operating sheet (RTP, OTP respectively), as well as the main design procedures (operators) related to calculations, layout, etc.) are used as input information. In figure 2.5 a toolkit diagram that provides the procedure for the formation of the object "Declarative Model of the TS" is presented. For designing a competitive TS design development trends and forecasts need to be considered design-technological type (corresponding blocks in a double frame). Declarative representing completely satisfying the preferences system, compared to each other, and then, based on the optimization procedures, the best variant of the TS is distinguished, being the result of choice. However, for complex technological systems to build a theoretical design that takes into account all developmental directions without isolating fragments of the TS seems practically unrealizable. Therefore, the designer should have the possibility of distinguishing between fragments that should change as a result of a change in value ideas, from fragments of the TS, which remain unchanged. This thesis leads to the necessity of distinguishing procedural represents about the TS and identifying the relationship between these two representation.
Fig. 2.5. Scheme of selection object “Declarative model”
2.4.3. Tools for the interaction of objects "Declarative model of TS" - "Procedural model of TS"

The interaction of two TS presents should be based on information about the trends of their development and improvement. Often these trends are taken into account spontaneously, non-systemically. Absent clearly regulated procedures that effectively implement this interaction. There is an apparatus "Target tree" [60, 61], with the help of which this interaction is systematized (figure 2.6). It is also significant that at the fragmentary level of TS representation, forward-looking solutions should be used, presented in the form of blocks in a double frame.

Fig. 2.6. Scheme of the interaction toolkit for TS objects “Declarative model-Procedural model”
2.4.4. Toolkit of the TS choice process

Figure 2.7 presents a generalized selection scheme based on the composition of the constituent fragments. The analysis of the resulting
scheme allows us to conclude about the feasibility of introducing into the arsenal of a modern designer for engineering forecasting toolkit and technical optimization. Entering such a tool should be in the form of autonomous subsystems that implement advanced design and optimization. This procedure is associated with determining the structure of subsystems, the main methods of forecasting and optimization, the features of application in the design tasks of modern TS.
3. RATIONAL CHOICE OF THE DESIGN FOR SPINDLE NODE SUPPORTS OF CNC MACHINES DRILLING- MILLING-BORING TYPE

In accordance with the rational choice methodology (Chapter 2), the procedure for designing spindle supports should not be reduced to a sequential analysis of the disadvantages and advantages of individual alternatives with calculation and extraction, but a components parallel design of the choice scheme (figure 2.3). According to the above-mentioned methodology, at the first stage, a set of alternatives (design variants) for spindle node (SN) on supports are formed using an appropriate toolkit.

3.1. Formation of project alternatives

A number of typical schemes of spindle nodes [2, 62, 63, 64] are known, classified by type of supports and their location. Figure 3.1 shows a fragment of such a classifier:

Already at the stage of selecting the supports type (rolling, hydrostatic, aerostatic, electromagnetic) information about selection criteria is needed, which are formed depending on the properties of the design options at the declarative and procedural model levels [44, 45]. At this initial stage, data on typical schemes (figure 3.1) are related to declarative knowledge. According to postulate 1 of the model of rational choice, the declarative model should reflect the information sufficient to build a procedural model. To clarify the integrated schemes it is necessary to implement the following sequence of steps.
For the case of the design of drilling, milling and boring machines, these Declarative models components must be supplemented with project requirements. The basic requirements include a sufficiently high statistical rigidity, reliability, and rapidity.

Fig. 3.1. Fragment of the node classifier: a – two-basic designs; b – three-support structures; c – nodes with front thrust bearings; d – nodes with rear axle bearings; e – units with installation of thrust bearings in the front and rear wall

Static load rating $C_0$, as the main characteristic of statistical rigidity for multioperational drilling, milling and boring machines should be not less than 20000 N, which provides advanced technological capabilities associated with the draft and finishing types of processing. The reliability of the bearing can be evaluating by the parameter of nominal durability, expressed either in the number of revolutions or in the form of time (resource) at a given constant speed, which the bearing must work through before the first signs of material fatigue for the bearing components appear. For the machines set considered, the value of nominal longevity $L_h$ should exceed 10000 hours.

Speed, as a characteristic of high-speed bearings, defined as the multiplication of the rotational speed on working dimension of the assembly should not be less than (4.5 ... 6.0)·$10^{-5}$ mm/min. According to set of evaluation criteria enlarged typical schemes most appropriate choice of supports on rolling bearings. Analysis of the spindle nodes
structures showed that in more than 90% of cases, sets of rolling bearings are used as supports. The remaining 10% is hydrostatic, hydrodynamic, aerostatic and electromagnetic. At the next stage, the type of rolling bearing is selected based on the direction of action of the perceived load. So for multioperational machines, where the combined load prevails (i.e. the load acting simultaneously on the bearing in the radial and axial direction, and both radial and axial load can be predominant) it is advisable to use radial-axial (RA) bearings. At the same time, depending on the loading scheme, radial (ball radial single-row bearings that can take both combined and axial loads) bearings can be used in the front and rear bearings. For angular contact ball bearing, the best compromise speed-rigidity is provided. For RA bearings with inclined contact, there are a number of series that differ in design and contact angle \( \alpha \). For example, the bearings of the company SNFA (Fr.) select 4 series:

1) BS – characterized by the contact angle \( \alpha = 62^0 \) and the perception of increased axial load;
2) V – \( \alpha = 15^0 \), which is characterized by reduced axial stiffness \( j_a \) and increased radial rigidity \( j_r \) (N/mm); effective at high speeds;
3) E-SE – \( \alpha = 25^0 \), which is characterized by large ratios \( j_r/j_a \) and work at medium speeds;
4) ED – \( \alpha = 15^0, 25^\circ \) with an improved design of the inner ring.

For the aforementioned series, the structural characteristics of the supports (number, nature of placement) should be specified. In modern constructions, duplex-, triplex-, and quarto-type connection schemes are increasingly used. The latter two are included in a schemes called “multiplex” (table 3.1).

1. Connection type duplex backs – DO (table. 3.1). This connection is symmetrical, capable of withstanding combined loads, including in the reverse mode. The large support surface provides the ability to withstand large tilting moments, allows for different preloads and contact angles \( \alpha \).

2. A duplex-type connection by the front (base) sides – DX (table 3.1). It is characterized by the same properties as the DO- connection, but
with greater achievable accuracy, the value of the permissible overturning moment decreases.

Table 3.1

<table>
<thead>
<tr>
<th>Connect type</th>
<th>Supports scheme</th>
<th>Symbol designation</th>
<th>Connect type</th>
<th>Supports scheme</th>
<th>Symbol designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duplex</td>
<td></td>
<td></td>
<td>Triplex</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DO</td>
<td>TD</td>
<td>DX</td>
<td>TF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DT</td>
<td>TDT</td>
<td>DT</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. A duplex-type connection according to the tandem method – DT-connection (table 3.1). It is characterized by the ability to withstand large axial unidirectional loads and the use of spring design preload. DT-connection assumes strict equality of angles contact. Under conditions of increased rigidity and high loads, a multiplex-type connection scheme is used (universal triplex TU, universal quart (4U), universal five (5U). Examples of such connections as triplex and quart are presented in table 3.1.

The increase in stiffness of spindle nodes directly depends on the presence and size of preload. When forming a set of design alternatives at the stage of creating preload, the issues of construction, mounting and size of preload are solved.
Preloading can be considered as an axial load that has a constant effect on the bearings in order to ensure contact between the spheres and the corresponding rolling grooves, reducing the effect of external loads. This load is applied mainly by means of an elastic element or by axial tightening.

To the main design preload options include:

1. Twinning of the angular contact Bearings Preload (BP1) in which the mating ends of the rings are ground to the amount needed to obtain a given preload after axial compression of the outer and inner rings with each other.

2. The use of bushings (BP2) of various lengths with two methods of mounting between the outer and inner rings. The difference in length of the bushings depends on the applied force magnitude and the overall dimensions of the working bearing working bodies and can be calculated analytically [63].

3. The use of gaskets (BP3) mounted between the inner and outer rings, the dimensions of which are determined similarly to the previous version.

4. The use of springs (BP4), based on the bearing ring, the design parameters of which can be determined analytically [42].

5. The use of a regulating nut or cap brought up to contact with the bearing ring (BP5), and then screwed on at a predetermined angle.

6. Adjustable device on the basis of a hydraulic cylinder (BP6). The increase in the initial set of design options may occur due to different types of mounting of the bearing supports, resulting in the application of the preload value. In the case of application of liner sleeves, there are two main types:
   - DD-mounting, associated with a decrease in the inner gasket ring to increase the preload and a decrease in the thickness of the outer gasket ring to reduce the preload;
   - FF-mounting, with the decrease in the thickness of the outer ring for increasing the preload and reducing the thickness of the inner ring to reduce it.
The mounting of bearings is related to the lubrication method, which ensures normal operation under conditions of considerable loads and temperatures. There are a number of methods to lubricate the supports, including:

1. A grease (plastic) lubricant (nFGL), characterized by its economy and ease of use, is applied for a long time (3 ... 5 or more years) with the greatest friction losses.
2. Oil bath lubrication (OBL), usually applicable to nodes with a horizontal spindle.
3. Power circulation (PCL) - closed, flow and mixed type.
4. Oil injection (IL) is a rather complicated structure in which the injection is carried out using nozzles, which allows to overcome the turbulence barrier created by the separator and balls.
5. Law lubrication (LL), characterized by costs order of several mg oil for each hour of operation, which is enough to ensure constant elastohydrodynamic scum; LL can be with additives that do not require recovery and do not pollute the environment.
6. Oil mist lubrication (OML) - a metered amount of pure oil is injected into the bearing, using filtered air as a means of moving the sprayed oil with drops of 0.2 μm.
7. Bearing lubrication using nozzles (NL) - is due to inertial forces (during rotation of the nozzle) and friction forces arising between the surface of the nozzle and oil, while the oil flows to the base of the cone, from the edge of which it breaks down and enters the bearing, either directly or through a channel provided in the housing wall.

The above methods can use different types of lubricants:

- calcium (CAL), on the basis of fatty greases or on the basis of synthetic fatty acids;
- silicone calcium (SCL) with high chemical stability;
- sodium (SKL), on the basis of fat constalins, having the ability to restore their plastic properties after cooling;
- sodium-calcium (SoCL), prepared from synthetic fatty acids;
- lithium (LL), characterized by increased water resistance;
- liquid grease (LG).

Different types of seals are used to protect the spindle supports:
- cap type (CTS);
- seals with friction elastic elements (EFS);
- seals with friction metal and graphite elements (MFS);
- centrifugal type and with screw grooves (AS);
- seals in the form of washers, annular gaps, grooves and labyrinths (LS).

Thus, the above 9 stages of the formation of project alternatives are necessary at the first stage of a rational choice. The diagram (figure 3.2) systematized these stages.

Here are some of the enlarged design alternatives of SN.

1. Two-support SN with twin angular contact bearings of ED series (ISO 0-10); Duplex type connection with front sides with preload in the form of two sleeves of various lengths, mounted according to the variant DD with grease lubrication (nFGL) and cap seals (CTL).

2. Two-support SN with dual angular contact bearings of type 2-46000; a duplex tandem connection with a spring preload with grease lubrication and a seal made of resilient dessected metal rings.

In a similar way, on the basis of experimental recommendations [67, 68, 69], it is possible to select a significant number of enlarged versions for design implementations, the components of which are shown in figure 3.2. When generating these options there is practically no need to use quantitative estimates, however, it is necessary to take into account forbidden combinations. The latter include:
- mounting of support type “duplex-tandem” of various bearings;
- the use of minimum lubrication for SN with relatively low speeds and significant dimensions, etc.
Fig. 3.2. Stages of project alternatives formation
The definition of forbidden combinations is carried out by the interaction of two components of a rational choice scheme (figure 2.3): “Variants of the TS” – “system of preferences”. Thus, the input of the “duplex-tandem” connection variant is determined by the criterion of dynamic load-rating. And for this design problem – milling of various types of surfaces is characterized by the presence of large axial unidirectional loads, under conditions of which the duplex-tandem connection functions well. It should be noted that the selection criterion mentioned above (dynamic load-rating) is the result of another decision act – on a set of choice criteria. In turn, the latter is solved by exchanging information with the components of the scheme – the “declarative” and “procedural” models.

3.2. Building a declarative model

To build a declarative model means to get a complete (working) description of the supports structures for the SN. Initial data is project requirements information and design documentation for a machine based on SF68PF4 – specialized four-coordinate drilling-milling-boring of standart size II. This machine is characterized by the following working space indicators:
- rotary table – ∅ 630 mm;
- the distance from the end of the horizontal spindle to the axis of the rotary table – 59 ... 441 mm;
- the distance from the end of the vertical spindle to the surface of the rotary table – 50...500 mm;
- distance from the spindle axis to the axis of the turntable – 205…295 mm.

Spindle node is characterized by indicators:
- rotation frequency \( n = 20 \ldots 4000 \text{ min}^{-1} \);
- the drive power of the main movement \( N = 7.5 \text{ kW} \);
- the greatest torque on the spindle – 307 N·m;
- tool – cone 40;
dimensions: $l = 312$ mm; $d = 65$ mm; $d_0 = 40$ mm.

For a single-row radial ball bearing of an especially light series with a nominal durability $L_h = 20000$ h (radial load $F_r = 4000$ N, rotation frequency $n = 4000$ min$^{-1}$), the bearing dynamic load rating $C$ is:

$$C = \frac{f_h}{f_n} \cdot F_r = \frac{3.42}{0.347} \cdot 4000 = 39400 \text{ N}.$$ 

Here $f_h$ is determined from the table at $L_h = 20000$ h. [62].

These conditions are satisfied bearing 2-46113E (EX65; ISO0-10) – one-piece with a bevel on the outer ring, the separator of which is centered on the double-sided inner ring. In the presence of angular contact bearings according to the DO scheme (figure 3.1) the nominal longevity is determined in the following sequence (the initial data in table 3.2)

Table 3.2

<table>
<thead>
<tr>
<th>Support</th>
<th>Load, N</th>
<th>X</th>
<th>Y</th>
<th>Dynamic load rating, $C$, N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radial, $P_r$</td>
<td>Axial, $P_a$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4000</td>
<td>700</td>
<td>1</td>
<td>1.92</td>
</tr>
<tr>
<td>2</td>
<td>2076</td>
<td></td>
<td>1</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Since $F_{r1}/2Y_1 = 1091$ N and $F_{r2}/2Y_2 = 698.75$ N, then $A > (F_{r1}/2Y_1 - F_{r2}/2Y_2)$ and the total axial load on support 1 is:

$$F_{a1} = l_2 F_{r2} + A = 0.86 \cdot 2076 + 700 = 2111 \text{ N}.$$ 

Here $l_2$ is determined by the data of [70]. Equivalent radial load on supports 1 and 2 is determined according to [71]:

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\[ P_1 = X_1 \cdot F_{r1} + Y_1 \cdot F_{a1} = 4000 + 1.92 \cdot 2111 = 8053 \text{ N}; \]
\[ P_2 = F_{r2} = 2076 \text{ N}. \]

In this case, the nominal longevity of the bearings:
- in support 1 with \( C_1/P_1 = 39400/8053 = 4.89; \)

\[ L_1 = \left( \frac{C_1}{P} \right)^3 = 117 \text{ mn.rev.}; \]

- in support 2 with \( \left( \frac{C_1}{P} \right)^3 = \left( \frac{37200}{2076} \right)^3 = 5754 \text{ mn.rev.}. \)

To determine the stiffness, it is necessary to calculate the total axial deformation (preload), which consists of axial deformations \( \delta_1 \) and \( \delta_2 \) of supports 1 and 2 [72]:

\[ \Delta = \delta_1 + \delta_2 = \left( F_{pl} / C \right)^2 \cdot \left( \frac{2}{1/i^3} + \frac{2}{1/i^3} \right), \]

where \( F_{pl} \) is the preload force, N:

\[ F_{pl} = 10^5 \sqrt{1.25d_m \cdot z \cdot \sin^2 \alpha}, \]

\( i_1, i_2 \) – the number of bearings mounted in the 1st and 2nd supports;

here \( d_m \) – diameter of the ball, mm; \( z \) – the number of rolling elements in the bearing; \( \alpha \) – the actual contact angle.

For angular contact ball bearings 2-46113E: \( d_m = 9 \text{ mm}; z = 24; \alpha = 26^0; F_{pl} = 340 \text{ N} \) (lightweight preload).

Axial stiffness \( j_a \) (N/mm) of a symmetrical support \( (i_1 = i_2 = 1) \) will be equal to

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where \( F_a \) – external axial force, N; \( \delta_a \) – axial displacement in the bearing, mm.

The maximum axial force at which the preload of one of the supports is completely removed:

\[
F_{a_{\text{max}}} = 1.5 \left[ 1 + \left( \frac{i_2}{i_1} \right)^2 \right] F_{pl},
\]

For a symmetric support, the last expression is represented as \( F_{a_{\text{max}}} = 3 F_{pl} \) and the axial stiffness in general form equals:

\[
j_a = k_i C^3 F_{pl}^{3/2},
\]

where \( k_i \) – coefficient that for a symmetric support \( (i_1 = i_2 = 1) \) is equal to 3 [72, 73].

For this version of the two-support symmetrical SN \( (i_1 = i_2 = 1) \), the stiffness characteristics are:

\[
C = 1.02 \times 10^6; \ \Delta = 0.0096 \text{ mm}; \ j_a = 2.12 \times 10^5 \text{ N/mm}.
\]

There are no uniform standards for assigning SN stiffness [62], however, based on ensuring the normal operation of bearings, the stiffness is 2.5 \( \times \) \( 10^5 \) ... 5.0 \( \times \) \( 10^5 \) N/mm. The above option does not provide normal operation.

As the second constructive option, choose the support in the form of twin bearings according to the DX scheme (table 3.1), the characteristics of which are:
\[ C = 1.02 \cdot 10^6; \Delta = 6.05 \cdot 10^{-3} \text{ mm}; j_a = 3.4 \cdot 10^5 \text{ N/mm}. \]

The second option falls into the range of recommended values.

As is known, the characteristics of the supports stiffness depend on the used SN scheme, the number of bearings in the support and the value of the preload. In table 3.3 shows the calculated data on the stiffness of the supports with different arrangement of bearings type 2-46113E.

Analysis of the table suggests that the last three options satisfy the requirements for the structures of spindle nodes in terms of rigidity.

The main criteria for the spindle nodes performance include compliance of the bearings accuracy rotation with the requirements for the accuracy of spindle nodes. For two-support SN (with arbitrary the number of bearings in one support) the ratio between the beating of the inner bearing rings and the beating of the spindle centering neck (or the conical spindle bore) is expressed by the following formula [62]:

\[
\Delta = 1.5 \left[ \frac{\Delta_1}{m} \pm \frac{1}{k} \left( \frac{\Delta_1}{m_1} + \frac{\Delta_2}{m_2} \right) \right],
\]

where \( \Delta_1 \) is the radial runout of the front support bearings, mm; \( \Delta_2 \) - radial runout of the bearings rear support, mm; \( k = l/a; l \) – intersupport distance; \( a \) – distance from the front support to the plane of measurement, mm; \( m_1, m_2 \) – the number of bearings in the front and rear supports.

As well known, for machine tools of accuracy B, the bearings of the front support are characterized by the accuracy class B (corresponds to class 2 at ISO and approximately AVEC 9 according to the USA standard B3.5), and the rear support according to class C (grade 4 ISO, AVEC 7).

Radial beating of the front and rear supports for these accuracy classes is determined from the table [62, 74, 75, 76]: \( \Delta_1 = 4 \cdot 10^{-3} \mu \text{m}; \Delta_1 = 6 \cdot 10^{-3} \mu \text{m}; \) the coefficient \( k = 52/312 = 0.17. \)
Table 3.3

<table>
<thead>
<tr>
<th>Bearing arrangement</th>
<th>$K_l$</th>
<th>Lightweight preload $F_{pl}$</th>
<th>Medium preload $F_{pl}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta \cdot 10^{-3}$</td>
<td>$j_a \cdot 10^3$</td>
<td>$j_r \cdot 10^3$</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>N/m m</td>
<td>N/m m</td>
</tr>
<tr>
<td>1 $i_1=1; i_2=1$</td>
<td>3</td>
<td>9.6</td>
<td>2.12</td>
</tr>
<tr>
<td>2 $i_1=2; i_2=1$</td>
<td>3.</td>
<td>7.8</td>
<td>2.75</td>
</tr>
<tr>
<td>3 $i_1=2; i_2=2$</td>
<td>4.8</td>
<td>6.1</td>
<td>3.4</td>
</tr>
<tr>
<td>4 $i_1=3; i_2=3$</td>
<td>6.2</td>
<td>4.6</td>
<td>4.35</td>
</tr>
</tbody>
</table>

The ratio of the accuracy of supports and spindle is calculated by the formula:

$$\Delta_1 = 1.5 \left[ \frac{4 \cdot 10^{-3}}{\sqrt{2}} \pm 0.17 \left( \frac{4 \cdot 10^{-3}}{\sqrt{2}} + \frac{6 \cdot 10^{-3}}{\sqrt{2}} \right) \right] = 0.0024...0.006.$$

Table 3.4 shows ratios for various bearing arrangements.

Table 3.4

<table>
<thead>
<tr>
<th>Bearing arrangement</th>
<th>Spindle’s conical hole runout, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i_1 = 1; i_2 = 1$</td>
<td>0.003±0.0086</td>
</tr>
<tr>
<td>$i_1 = 2; i_2 = 1$</td>
<td>0.002±0.0065</td>
</tr>
<tr>
<td>$i_1 = 2; i_2 = 2$</td>
<td>0.002±0.0066</td>
</tr>
<tr>
<td>$i_1 = 3; i_2 = 3$</td>
<td>0.002±0.0049</td>
</tr>
</tbody>
</table>
Known mutual orientation techniques the eccentricities of the bearing rings can be achieved a noticeable reduction in runout – the lower limits of accuracy are given in table 3.4. Virtually all schemes presented in table 3.4 meet the allowable radial runout of the conical bore of the machine spindle of high accuracy class \([\Delta]= 0.005 \text{ mm}\) (provided that it is correctly mounted).

Formation of full design options constitute the basis of the declarative model in the rational choice procedure, it is impossible without defining the method and support grease designs. At the stage of the initial formation of design alternatives, possible lubrication methods are listed. Not all of these methods are applicable in the construction of high-precision, high-speed machines. The area of rational use is limited by the high speed, characterized by the number \(d \cdot n_{\text{max}}\), where \(d\) – diameter of the bearing bore in mm; \(n_{\text{max}}\) – the maximum number of revolutions, or the number of \(d_m \cdot n_{\text{max}}\), where \(d_m\) – the mean diameter of the bearing.

For this case, the consideration at the location at the front end bearing 113 – \(d = 65 \text{ mm}; d_m = 82.5 \text{ mm}; n_{\text{max}} = 4000 \text{ min}^{-1}\).

The magnitude of the rapidity \(d \cdot n_{\text{max}} = 260000 \text{ mm} \cdot \text{min}^{-1}\) and \(d_m \cdot n_{\text{max}} = 330000 \text{ mm} \cdot \text{min}^{-1}\) allows us to make judgments about the applicability of lubrication methods. So the liquid lubricant in the oil is limited by the number of \(d_m \cdot n_{\text{max}} = 100000 \text{ mm} \cdot \text{min}^{-1}\), which is unacceptable. On the other hand, such methods as oil injection, minimal drip lubrication and oil mist are applicable at high speeds \((d_m \cdot n_{\text{max}} > 750000 \text{ mm} \cdot \text{min}^{-1})\).

In the desired design limits, circulation lubrication (natural and forced) is mainly used, which provides the necessary lubricant consumption through the bearing, and includes a cooling system, according to the condition of the heat removal.

Along with liquid lubricants, greases are also used, which are limited to relatively small high-speed numbers. So for the considered angular contact ball bearings of the 46000 series with a contact angle of \(26^\circ\), the maximum speed is in the range of: \(d \cdot n_{\text{max}} = 220000 ... 320000 \text{ mm} \cdot \text{min}^{-1}\), which is suitable for this of the design variant \(d \cdot n_{\text{max}} = 260000 \text{ mm} \cdot \text{min}^{-1}\).
Grease lubricants must have good lubricating properties, resist aging well and reliably protect the bearing from corrosion. The required volume of lubricant $V$, $\text{m}^3$ is calculated by the formula [62]:

$$V = f \frac{B \cdot d_p}{1000} \cdot 10^{-4},$$

where $B$ – width of the bearing, mm; $f$ – coefficient depending on the size of the bearing; $f = 1.0$ at $d = 40 \ldots 100$ mm.

Volume $V$ for the design variant will be

$$V = 1.0 \frac{18 \cdot 82.5}{1000} \cdot 10^{-4} = 1.49 \cdot 10^{-4} \text{ m}^3.$$

The use of high-quality lubricants makes it unnecessary to replace it during the entire service life.

The quality of greases is estimated by the penetration rate - the number of penetration. In the design variants, lithium greases are used, such as TsIATIN-202 with a penetration number in the range of 285…315.

The choice of the type of lubricant, the location of the spindle assembly and the operating conditions dictate the type of seal. So with the horizontal arrangement of the spindle, grease lubrication of the bearing, most often used labyrinth seals contactless type. For protection of bearings in particularly difficult conditions at low and medium speeds, it is reinforced with lip seals and, conversely, gap seals are used to protect the SN operating in favorable (for pollution) conditions.

Thus, the main invariant of the declarative model is a complete description of the design alternative of the SHU, which details the enlarged one, which is an invariant of the design alternative choice block (“SU Variants, figure 2.3).
As an example of such an implementation, let us give a design alternative to the SN of a specialized four-axis cantilever milling and drilling machine based on the SF68VF4 model.

Two-support symmetric design of SN on rolling bearings:
- overall dimensions \( l = 312 \text{ mm}, a = 52 \text{ mm}, d = 65 \text{ mm} \); rotational accuracy of the tapered bore \( \Delta_1 = 0.002 \text{ mm} \);
- front bearing: duplexed bearings with inclined contact \( \alpha = 26^\circ \), series 46000, 2th accuracy classes of ISO, duplexed with the front sides (DX) with a preliminary average preload \( F_{pl} = 630 \text{ N} \) in the form of gasket bushings and mounted according to the DD method. Main characteristics of bearings: nominal durability \( C_1 = 117 \text{ million rev.} \) (with a dynamic load \( P_1 = 39400 \text{ N} \)); axial rigidity \( j_a = 4.1 \cdot 10^5 \text{ N/mm} \) and radial rigidity \( j_r = 8.76 \cdot 10^5 \text{ N/mm} \);
- rear bearing: duplexed bearing of 4th accuracy class of the same series with a slight preload \( F_{pl} = 340 \text{ N} \) with the same mounting method. Main characteristics: nominal durability \( C_2 = 5754 \text{ million rev.} \) (\( P_2 = 37200 \text{ N} \)); axial and radial stiffness \( j_a = 3.4 \cdot 10^5 \text{ N/mm}; j_r = 7.14 \cdot 10^5 \text{ N/mm} \).

Bearing grease – consistent with a volume of \( 1.49 \cdot 10^{-4} \text{ m}^3 \) for one bearing and penetration number of about 300 units.

Seal – labyrinth, contactless type.

A specific feature of the declarative model is the requirement for the mutual completeness of information, which is interpreted as providing a process for constructing procedural knowledge intended to modify (improve) the design on the basis of existing priorities.

### 3.3. Build a procedural model

So, we will consider the script of constructing a procedural model. It begins with an analysis of the project situation by the forecast type and the selection of the performance criterion (figure 2.3). A parallelism of the rational choice scheme is that the decision making of a particular criterion depends on the data of the declarative model.
So the need to increase the accuracy of processing products leads to the need to increase the working speeds, including the output at the rotational speed \( n = 6000 \ldots 8000 \text{ min}^{-1} \). Increasing the working modes leads to a change in the basic options presented in the declarative model.

The first component of the procedural model is the connection diagram of the bearings in the support. For high-speed machines, SN structures are used, in which axial loads are perceived by the front support, while the back is floating.

Figure 3.3 shows four alternative options for the implementation of high-speed machine supports [63]

![Diagram of support schemes](image)

Fig. 3.3. Scheme supports of high-speed machines:
- a – DX scheme;
- b – Tandem-X scheme;
- c – X-shaped scheme;
- d – Tandem-O scheme

Promising for this option is duplexing according to the tandem method (figure 3.3, b), which involves the selection of identical bearings and the use of lower preloads. The latter makes it possible to increase the maximum speeds with similar loads.

In the general case, the magnitude of the axial deflection \( \delta_{aT} \) for tandem scheme is reduced by more than a third:

\[
\delta_{aT} = \delta_{a0} \cdot w,
\]
where $\delta_{a0}$ – axial deflection of a separate bearing, mm;

$w$ – coefficient depending on the number of bearings $i$ in the support; for $i = 2 \rightarrow w = 0.63$.

Thus, the axial deflection $\delta_{aT}$ will be equal: $9.4 \cdot 0.63 = 5.9 \mu m$. Such an axial deflection corresponds to a certain value of the preload force $F_{pl}$

$$F_{pl} = 10 \cdot \frac{\delta_{aT}^{2/3} \cdot d_m^{1/2} \cdot \sin^{5/2} \alpha}{2^{2/3}} = 460 \, N.$$ 

In this case, the axial stiffness $j_{aT}$ of the symmetric support ($i_1 = 1; i_2 = 1$) will be equal to

$$j_{aT} = 3 \cdot C^{2/3} \cdot F_{pl}^{1/3} = 2.35 \cdot 10^5 \, N/mm.$$ 

The total axial deformation $\Delta_T$ (preload) of the support 1 and the support 2 will be equal to

$$\Delta_T = \left( \frac{F_{pl}}{C} \right)^{2/3} \cdot \left( \frac{1}{i_1^{2/3}} + \frac{1}{i_2^{2/3}} \right) = 0.0118 \, mm.$$ 

For a symmetrical support according to the tandem scheme with single bearings, the achievable axial stiffness is 10% higher than according to the DX-scheme, but it is not included in the recommended values $\delta = (2.5 \ldots 5.0) \cdot 10^5 \, N/mm$.

For the version of bearings on duplexed bearings, according to the tandem-scheme gives:

$$j_{aT} = \frac{i}{8 \cdot C^{2/3}} \cdot F_{pl}^{1/3} = 3.75 \cdot 10^5 \, N/mm; \quad \Delta_T = 0.0074 \, mm.$$
These values of stiffness characteristics are in the recommended range.

Since the magnitude of the rapidity \( d \cdot n_{max} \) for the variable variant increases to values \( d \cdot n_{max} = 455000 \text{ mm} \cdot \text{min}^{-1} \), then the circuit in figure 3.3, but can not be implemented with grease. For such speeds \((4.2 \ldots 6 \cdot 10^5 \text{ mm} \cdot \text{min}^{-1})\) [62] it is advisable to use the method natural circulation with low-viscosity oils whose value is: \( v = (12 \ldots 23) \text{ cSt (centistokes)} \), or in the SI system: \( v = (12 \ldots 23) \cdot 10^{-6} \text{ m}^2/\text{s} \).

The choice of circulation lubrication implies the elaboration of a cooling system (natural or artificial) of a general or autonomous type. For an expensive refrigeration system, thermal control can be performed. It is also necessary to make structural changes in the bearing housing:

- drain holes, the lower edge of which is located at the level of the center of the lower rolling body in the bearing;
- oil cans, oil glasses or float oil indicators to monitor the level of oil;
- special cavities for creating the necessary oil reserves in the housing, as well as cavities for the accumulation of dirt, and hence the openings for the release of used oil;
- channels designed to circulate oil in the housing;
- the felt traffic jams providing an oil filtration.

High-speed SN work exclusively with non-contact seals. The presence of a circulating fluid lubricant predetermines a number of requirements for seals:

- symmetry, eliminating the pumping effect and the removal of oil particles from the spindle assembly;
- precise centering relative to the surface of rotation and, as a result, providing a radial clearance of 0.2 \ldots 0.3 \text{ mm} (in the case of fastening on the thread, cylindrical belts should be provided);
- blowing air through seals;
- the presence of oil collectors and channels for drainage of lubricant;
- strengthening by an external protective ring in case of intensive external pollution;
- the use of oil deflectors and oil breakthrough threads (shallow annular grooves with a triangular profile) under contaminated conditions.

The design of the lubrication and cooling system along with the analysis of prototypes is associated with the elaboration of patent information, which is mainly concentrated in classes B23Q IPC (International Patent Classification) and their subheadings: B23Q1/00 (9/00) – the main components of the machines; B23Q11/00 (13/00; 27/00) – auxiliary equipment, protective or safety devices; B23Q11/12 – device for cooling and lubrication of machine parts; B23Q11/14 – means to maintain a constant temperature.

Analysis of the patent fund makes it possible to select several options for cooling structures:

1. Special device covering heat-receiving elements (patent application (PA) N2-5545 from 02.02.90, Japan);
2. With the help of a refrigerant whose consumption is regulated measuring signal controlled valves (PA. N348715 from 01.03.90, France);
3. In the form of a glass with an annular hollow chamber, filled with liquid, providing a closed cooling cycle: steam-condensate (PA. N3-4343 from 01.22.91, Japan);
4. A device that dispenses the flow rate of the cooling medium by means of the hydraulic drive valve, depending on the actual cutting speed (PA. N2-78975, from 11.07.90, DD).

Thus, the procedural model of this project task includes a number of variable elements of SN supports that achieve a certain improvement goal.

Decision sequence is presented as an iterative procedure, at each stage of which the following is performed:

1) Selection of basic alternatives based on the interaction of objects: “Declarative model – Priority system”.
2) Modification (and addition) of the forecast data for the initial variants through the use of structural elements of the procedural model
3) Selection of a rational variant of the designed structure using optimization methods.

3.4. The choice of a rational option spindle node

Using the above script, it is possible to propose a SN design on two symmetrical bearings, each of which represents duplexed rolling bearings in a tandem scheme with a preload value of $F_{pl} = 460$ N. Characteristics of support stiffness take the following values: axial deflection $\delta_{aT} = 5.9 \mu$m; axial deformation $\Delta_T = 0.0074 \mu$m; axial stiffness $j_{aT} = 3.75\cdot10^5$ N/mm. The speed of this variant of the SN is $4.55\cdot10^3$ mm-min$^{-1}$; circulating lubricant; low-viscosity oil $v = 12\cdot10^{-6}$ m$^2$/s; non-contact seal labyrinth type with an oil strainer; cooling with refrigerant, the flow of which is regulated by valves (PA. N0348715 from 1.03.90, France).

3.5. Features of the design of the spindle node supports

When designing machine tool supports for durability criteria, bearings are selected from among standard ones bearing by dynamic load rating. The specifics of calculating shaft bearings and machine spindles is to take into account the additional load on the bearing from preload and from the unit operation at higher rotational frequencies. For most machine tool bearings, the following working conditions are typical: on the shaft there are a group of driven gear wheels and a tool block. During
the entire service life of the spindle bearings, the machine operates at different speeds. At each spindle speed, one of the driven gears operates. Thus, each of the spindle bearings at different time intervals of work are under the action of loads different sizes. Accounting for mode variability is determined by the equivalent load at the most unfavorable from one of the driven gears and the corresponding cutting condition.

For twin angular contact bearings mounted on the spindle back support of the forming unit, the calculation takes into account the basic static load rating equal to twice the static load rating of one bearing. In turn, the dynamic load capacity $C_r$ of a set of dual (specially selected at the factory) angular contact bearings according to schemes X (“available”; front sides) is taken as for one double row. The total dynamic load rating $C$ of a set of two ball bearings is assumed to be $1.62C_r$.

Bearings mounted on an X-shaped scheme may have different preloads, as well as variable contact angle. In contrast to the O-shaped scheme, this scheme is characterized by a more limited ability to withstand tilting moments. As a consequence, the limited bearing surface reduces both the rigidity of the system and the possible misalignment.

To assess the performance of the spindle bearings, we use the APM Bear module [77], which performs a comprehensive analysis of rolling bearings, calculating the main characteristics of the bearings and ensuring the selection of the optimal design of the bearing assemblies. A feature of this module is the representation of the bearing in a non-ideal version, taking into account the errors in the manufacture of rolling elements and the raceways of the bearing. Such a consideration is typical for many problems of contact stiffness and contact stresses. The APM Bear performs the full range of verification calculations, when the output characteristics of the bearing are calculated from the known bearing geometry. At the same time, original analytical and numerical approaches are used, as well as methods of mathematical modeling, which makes it possible to present the results of the calculation of these parameters and
the values of their statistical dispersion in a user-friendly form – tables, graphs, histograms.

In figure 3.4 presents a comprehensive calculation of duplexed bearings with inclined contact $\alpha = 26^0$, series 46000, 2th classes of accuracy of ISO in the front support.

Fig. 3.4. Calculation of angular contact bearings in CAD APM Bear
3.6. Optimization of the spindle node design by the LP-search method

For the selected SN constructions, we will perform a search for optimal sizes – multicriteria four-parameter optimization by the LP-search method [19, 20, 57].

1. Construct N vectors in four-dimensional space:

\[ x_l = \{d_1, l_1, l_{p1}, l_{z1}\}, \ldots, x_N = \{d_N, l_N, l_{pN}, l_{zN}\}, \]

where \( l_p, l_z \) – the distance between the bearings in the front and rear bearings; \( d, l \) – diameter and interfacing distance.

In design calculations, it is recommended to take \( N = 128; 256 \).

2. Accept as the basic design option SF68PF4:

\[
\begin{align*}
  d &= 65 \text{ mm}; \ l_p = l_z = 3.2 \text{ mm}; \ l = 312 \text{ mm}; \ l = 55 \text{ mm}; \\
  l_k &= 70 \text{ mm}; \ l_f = 12 \text{ mm}; \ a_0 = 0.3\cdot10^{-8}, 1/N\cdot\text{mm}; \\
  A_0 &= 2.3\cdot10^{-5} \text{ mm}/N; \ E = 2.1\cdot10^5 \text{ MPa}; \ f = 19 \text{ Hz}; \ \lambda = 0.27.
\end{align*}
\]

3. We impose restrictions on optimized variables:

\[ 34 \leq d \leq 120 \text{ (mm)}; \ 150 \leq l \leq 500 \text{ (mm)}; \]
\[ 0 \leq l_p \leq 30 \text{ (mm)}; \ 0 \leq l_z \leq 60 \text{ (mm)}. \]

4. The vector of values of the parameters to be optimized will be determined by the following dependency (for example, the spindle diameter):
\[ d = d^* + (d^{**} - d^*) \cdot q_{ij} \]
\[ d_1 = 34 + (120 - 34) \cdot \frac{1}{2}; \]
\[ d_7 = 34 + (120 - 34) \cdot \frac{112}{128}, \]

where \( d^* \) – the minimum spindle diameter for a given machine size; \( d^{**} \) – the maximum value of the diameter; \( q_{ij} \) - Cartesian coordinates of points \( Q \) of the space of parameters to be optimized:

\[ q_{ij} = e_1 V_j^{(1)} \ast e_2 V_j^{(2)} \ast ... \ast e_m V_j^{(m)}, \]

where \( i = 128; j = 4; \ast \) – the sign of the bitwise addition by modul 2 in the binary system;
\[ V_j^{(l)} = r_j^l \cdot 2^{-l} \] – guides numbers;
\[ r_j^l \] – numerators of guide numbers [4];
\( l \) – the number of the binary segment (if \( N = 128 \), then \( l = 7 \), since \( 2^7 = 128 \)).

5. Calculate the values of the efficiency criteria at each point in the space \(< d_1, l_1, l_{p1}, l_{z1}>\). As the performance criteria for the spindle node we take:

a) elastic radial displacement \( \Delta \) from the unit force of the front end of the spindle, due to the compliance of the spindle and its supports;
b) the reduced load on the front support of the spindle \( R_p \) from the unit force at its front end;
c) the maximum radius vector \( A_m \) Amplitude Phase-Frequency Characteristic (APFC) on perturbation from the cutting force in the radial direction at the main frequency.

The analytical expression of the efficiency criteria \( \Delta, R_p, A_m = f(d_i, l_i, l_{pi}, l_{zi}) \) is given in [78].

6. Sort the values of the criteria ascending and draw up a test table (Table 3.5).
Each row of the table corresponds to one of the particular criteria, and in the numerator is indicated the number of the $i$ variant for the spindle node, in the denominator the normalized value of the particular criterion corresponding to this variant.

Rationing is carried out in accordance with the expression:

$$\lambda_i = \frac{y_k(Q_i)}{\min y_k},$$

where $y_k$ is a particular criterion of efficiency.

<table>
<thead>
<tr>
<th>Test results table</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta$</td>
</tr>
<tr>
<td>$\lambda^1$</td>
</tr>
<tr>
<td>$\Delta$</td>
</tr>
<tr>
<td>$\lambda^2$</td>
</tr>
<tr>
<td>$\Delta$</td>
</tr>
<tr>
<td>$\lambda^3$</td>
</tr>
</tbody>
</table>

In the normalized expression $\min y_k \neq 0$ – is the smallest value of $y_k$ from all obtained in the calculations. For some option (first left, table 3.5):

$$\lambda_i = \lambda_{\min} = 1$$

Value $\lambda^i_k$ to characterize the options in terms of their proximity to the best option for each of the criteria.

In Table 3.5 shows the border (double broken line), to the left of which there is an area of feasible solutions. In this case, there are only two solutions in this area - options 21 and 14. With a slight increase in the tolerance for the restriction introduced earlier on $R_p$, the solution 31 can also be included in the area of permissible solutions. Table 3.6 shows
the values of the controlled parameters for options 21, 14 and 31, as well as the parameters of the basic SN option.

Table 3.6

<table>
<thead>
<tr>
<th>Variant, N</th>
<th>$d$</th>
<th>$l$</th>
<th>$l_f$</th>
<th>$l_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>65</td>
<td>312</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>21</td>
<td>37</td>
<td>336</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>14</td>
<td>101</td>
<td>423</td>
<td>20</td>
<td>28</td>
</tr>
<tr>
<td>31</td>
<td>72</td>
<td>347</td>
<td>2</td>
<td>26</td>
</tr>
</tbody>
</table>

For all the above options are characterized by different values of $l_p$ and $l_z$, and there is a tendency to reduce the size of $l_p$ and increase the size of $l_z$. The convergence of bearings in the front support increases its rigidity, and an increase in $l_z$ increases the pinching effect of the rear support. The choice of the final version is carried out by the designer on the basis of this test table. This selection will be made based on parametric design changes during the optimization process.

3.7. Use rational choice in the problem of optimization of cutting conditions

Consider the task of finding the optimal modes of two-pass milling on the machine SF68VF4 ensuring a minimum cost of $C_2$ [79, 80, 81].

Form the objective function

$$C_2 = B \cdot t_{M1} + \frac{(B \cdot t_c + B_T) \cdot t_{M1}}{T_1} + B \cdot t_{M2} + \frac{(B \cdot t_c + B_T) \cdot t_{M2}}{T_2},$$

(3.1)

where $B$ – unit cost of machine time cent/min; $B_T$ - reduced costs due to the operation of the cutting tool for the period of its durability; $t_{M1}$, $t_{M2}$ – cutting time, respectively, on the first and second manufacturing step; $t_c$ – tool change time; $T_1$, $T_2$ – tool life period, respectively, on the first and second step.
Initial data. The workpiece – cast iron SCh15 GOST 1412-85; tool - end mill with taper shank 2223-0147, \( d = 32 \) mm; \( z = 6 \); \( \gamma = 15^0 \); \( \rho = 3 \) mm; \( t = 5.5 \) mm.

The objective function \( C_2 \), taking into account the accepted initial data, is represented as follows:

\[
C_2 = \frac{L}{s_{z1} \cdot Z \cdot n_1} \cdot i + \left( B \cdot (t_c + B_t) \right) \cdot \frac{L \cdot i \cdot \left( \frac{\pi d}{1000} \right) \cdot \left( \frac{1}{m} \cdot n_1 \left( \frac{1}{m} \right)^{-1} \cdot t_1 \cdot s_{z1} \left( \frac{y}{m} \right)^{-1} \cdot B \cdot m \cdot Z \cdot m \right)}{(C_v \cdot K_v) \cdot \frac{1}{m} \cdot d \cdot m} + \\
\frac{B \cdot L}{s_{z2} \cdot Z \cdot n_2} \cdot i + \left( B \cdot (t_c + B_t) \right) \cdot \frac{L \cdot i \cdot \left( \frac{\pi d}{1000} \right) \cdot \left( \frac{1}{m} \cdot n_2 \left( \frac{1}{m} \right)^{-1} \cdot t_2 \cdot s_{z2} \left( \frac{y}{m} \right)^{-1} \cdot B \cdot m \cdot Z \cdot m \right)}{(C_v \cdot K_v) \cdot \frac{1}{m} \cdot d \cdot m}
\]

(3.2)

where \( L = l + l_1 + l_2 \) – the length of processing; \( i \) – the number of passes; \( s_{z1}, s_{z2} \) – feed per tooth, respectively, on the first and second passes; \( Z \) – the number of teeth cutters; \( t_1, t_2 \) – depth of cut in the first and second passes; \( B \) – width of milling.

The exponents and dependency coefficients are determined by reference:

\( C_v = 72.0 \); \( q = 0.7 \); \( x = 0.5 \); \( y = 0.2 \); \( u = 0.3 \); \( p = 0.3 \); \( m = 0.25 \) ([81], t. 39, p. 286), \( K_v = 1 \); \( l_1 + l_2 = 14 \) ([82], Appendix 4, sheet 5, p. 373); \( B = 3.82 \) \( \varphi \); \( B_T = 0.63 \) \( \varphi \); \( t_C = 1 \) min.

Using reference data allows you to specify the objective function

\[
C_2 = 75.28 \cdot s_{z1}^{-1} \cdot n_1^{-1} + 2.49 \cdot 10^{-10} \cdot s_{z1}^{-0.2} \cdot n_1^{3} + \\
+ 75.28 \cdot s_{z2}^{-1} \cdot n_2^{-1} + 2.48 \cdot 10^{-12} \cdot s_{z2}^{-0.2} \cdot n_2^{3}
\]

(3.3)
On figure 3.5 shows the level lines of the function \( C_I = f(s_{z1}, n_1) \), characterizing the position of extr in the two-dimensional parameter space \( \{s_Z, n\} \). To display the level lines, use the operator "Contour" in the MATLAB software environment.

![Figure 3.5](image)

**Fig. 3.5.** Cost of two-pass processing: a – function graph; b – level lines

*Technical restrictions* imposed on the objective function governing the force when milling on roughing and roughness machined surface to clean.

\[
s_{z1} \leq \frac{[P] \cdot d^q \cdot n^w}{10 \cdot C_p \cdot t^y \cdot B^u \cdot Z \cdot K_{MP}} = 0.31, \tag{3.4}
\]

where \([P]\) – allowable force; \(C_p, K_{MP}\) – coefficients reflecting the influence of other factors unaccounted for in this formula on the cutting force.

\[
R_a = 4.83 \cdot \left( \frac{s_{z2}^{1.69} \cdot t_2^{0.15}}{V_2^{1.23} \cdot \rho^{0.14} \cdot \gamma^{0.46}} \right) \leq R_a^H
\]

After substituting the initial data at \( t_2 = 0.5 \) mm and \( R_a = 1.25 \) μm, we obtain the constraint:

\[
s_{z2}^{1.69} \cdot n_2^{-1.23} \leq 2.42 \cdot 10^{-4} \tag{3.5}
\]
We present the constraints (3.3) and (3.4) to the form used in geometric programming (GP):

\[
3.27 \cdot s_{z}^{0.74} \leq 1; \\
2.28 \cdot 10^{4} s_{z}^{1.69} \cdot n^{-1.23} \leq 1
\]  

(3.6)

The direct formulation of GP (3.3) can be brought to dual formulation

\[
V(w) = \left(\frac{72.58}{w_{01}}\right)^{w_{01}} \cdot \left(\frac{2.49 \cdot 10^{-10}}{w_{02}}\right)^{w_{02}} \cdot \left(\frac{72.58}{w_{03}}\right)^{w_{03}} \cdot \left(\frac{2.49 \cdot 10^{-10}}{w_{04}}\right)^{w_{04}} \\
\times 3.27^{w_{11}} \cdot \left(2.28 \cdot 10^{4}\right)^{w_{21}} \rightarrow \max
\]

with constraints such as the normalization condition and orthogonality:

\[
\begin{align*}
-w_{01} + 3 \cdot w_{02} &= 0 \\
-w_{01} + 0.2 \cdot w_{02} + 0.74 \cdot w_{11} &= 0 \\
-w_{03} + 3 \cdot w_{04} - 1.23 \cdot w_{21} &= 0 \\
-w_{03} \cdot 0.2 \cdot w_{04} + 1.69 \cdot w_{21} &= 0 \\
w_{01} + w_{02} + w_{03} + w_{04} &= 1
\end{align*}
\]  

(3.7)

Since the problem of the 1st-degree of difficulty \((m = 4, n = 6)\) under consideration, the system of linear equations (3.7) does not have a unique solution. Using the Wilde method [5], we define the dual weights of \(w\). To do this, we solve the system (3.7) with respect to the least significant cost component (the fourth pozinom of the objective function characterized by the dual weight \(w_{04}\)).
\[
\begin{align*}
  w_{01} &= 0.75 - 1.99 \cdot w_{04} \\
  w_{02} &= 0.25 - 0.66 \cdot w_{04} \\
  w_{03} &= 1.65 \cdot w_{04} \\
  w_{11} &= 1.08 - 2.85 \cdot w_{04} \\
  w_{21} &= 1.1 \cdot w_{04}
\end{align*}
\]

(3.8)

In order for all \( w \) to be positive (a necessary condition of the GP), the value of \( w_{04} \) must be within: \( 0 \leq w_{04} \leq 0.3789 \).

Let us represent \( V(w) \) as a function of \( w_{04} \) and using the dichotomy method or the operator (m-file) "fmin" MATLAB, we define the upper boundary of the dual function \( V(w) = 1.37 \) and the value of the dual weight \( w_{04} = 0.1 \) maximizing the objective function: \( w_{04} = 0.1 \). Solving the system (3.8), we define the values of dual weights:

\[
w_{01} = 0.55; w_{02} = 0.18; w_{03} = 0.17; w_{04} = 0.55; w_{11} = 0.29; w_{21} = 0.11.
\]

The values the cutting optimal modes \( \{n, s_z\} \) we define from the conditions of partial invariance:

\[
\begin{align*}
  72.58 \cdot s_{z1}^{-1} \cdot n_1^{-1} &= 1.37 \cdot 0.55 \\
  3.27 \cdot s_{z1}^{0.74} &= 1 \\
  72.58 \cdot s_{z2}^{-1} \cdot n_2^{-1} &= 1.37 \cdot 0.17 \\
  2.28 \cdot 10^4 \cdot s_{z2}^{1.69} \cdot n_2^{-1.23} &= 1.
\end{align*}
\]

(3.9)

The values of the optimal cutting modes \( \{s_{z10}, n_{10}, s_{z20}, n_{10}\} \) are determined by solving the system of equations (3.9)

\[
\begin{align*}
  n_{10} &= 481.62 \text{ rpm}; s_{z10} = 0.2 \text{ mm/tooth}; V_{10} = 48.41 \text{ m/min}; \\
  n_{20} &= 1906 \text{ rpm}; s_{z20} = 0.16 \text{ mm/tooth}; V_{20} = 191.61 \text{ m/min}.
\end{align*}
\]

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The minimum cost value of two-pass processing takes the magnitude: $C_2 = 1.37 \xi$.

It should be noted that the magnitude of the speed $V_{20}$ is overestimated in comparison with the recommended [82, 83, 84]. In accordance with the scheme of rational choice (Chapter 2), it is necessary to apply interaction tools for the contour “Declarative model (DM)” → “System of preferences” → refined “Declarative model” (figure 2.3).

Analysis of the machining process at high cutting speeds along with roughness problems shows the need to take into account temperature factor (element of the system of preferences). This is due to the shift of the wear mechanism (from abrasive and adhesive to thermal and diffusion) and to the effect of temperature distortions on the manufactured part quality. This accounting is carried out by updating the procedural model, which contains information on technical constraints on optimized variables and criteria (not reflected in the declarative model). In particular, the temperature limitation ($^0K$) when machining the end mill (material of the cutting part R6M5 – HSS type M2) of a gray iron workpiece is described by the dependency [58]

$$\theta^0 = 490 \cdot \left( \frac{\pi d}{100} \right) \cdot n_2^{0.2} \cdot s_2^{0.12} \cdot t_2^{0.09} \leq [\theta^0],$$

where $[\theta^0]$ – limiting temperature in the cutting zone, $^0K$; $d$ – diameter of the cutter.

It should be noted that as a result of using the “DM–PM” interaction toolkit the above temperature limit goes into a refined formulation of the optimization problem and already applies to information of declarative type. The initial use of it as a declarative was not appropriates (an increase in the degree of difficulty, etc.). This information is transformed according to the rational choice toolkit only after receiving the intermediate design solutions.
The use of temperature limitation is not allows you to use the apparatus of geometric programming, because constraint weights $w_{ij}$ ($i \neq 0$) take negative meaning. Due to the fact that the introduced restriction becomes active, the speed at the finishing stage is $V = 82.4$ m/min ($n = 820$ min$^{-1}$). The cost varies slightly $C_2 = 1.4$ €.
4. INFORMATION SUPPORT OF THE PROCESS FOR
CONSTRUCTION OF TECHNOLOGICAL SYSTEMS

4.1. Features of information support

The proposed rational choice methodology (Ch. 2) predetermines a
certain system and set of rules for developing information support for a
Technological System project, which is understood as a set of methods
and means of selecting, classifying, storing, searching, updating and
processing information, as well as a set of primary and derived data used
for predictive information. First of all, this methodology confirms the
expediency of distinguishing two main information systems: potential,
containing data that are invariant with respect to the considered design
object, and target system, reflecting the dynamics of the object’s
development, and including flows of generated design and engineering
solutions oriented to this object. Potential information system includes:

- arrays of normative-reference information – GOST, norms, classifier
classifiers, etc;
- arrays of design data taken from drawings, specifications of
technological system components, including prototypes;
- arrays of technological data describing the methods of
manufacturing, fixtures, tools and technological environment.

Formation of normative-reference information arrays carried out, as
a rule, using matrix structures with non-hierarchical keys (identifiers).
The implementation of such structures in general form are arrays of
characteristic values and characteristics of the form.
where $z_{ij}$ – value of $j$-st feature of the $i$-st object (for example, in the array of materials – the value of the material grade attribute); $\mu_{ij}$ – value of the $j$-st property for the $i$-st material.

In contrast to the arrays of normative and reference information, the formation of arrays for design, technological and running data should allow the creation of certain ordered sets of the dynamic series type on their basis. The compilation of the dynamic series is preceded by the ordering of the various parameters $q$. These include streamlining in time and according to various technical and economic characteristics, such as power, performance, etc. To implement this streamlining, a hierarchical key is introduced [85, 86] in the form of the following syntactic structure (to streamline data on the components of technological systems)

$$s_1^t, s_2^t, ..., s_n^t, N_1^2, N_2^2, ..., N_m^2, t_1^3, t_2^3, ..., t_k^3,$$

where $s_i^t$ – type of objects under study; $N_j^2$ – technical-economic parameter of the object; $t_h^3$ – year of construction, affixed to the drawing.

This hierarchical key corresponds to the hierarchical arrays of the realizations, the attributes included in them and, as a consequence, the hierarchical data structures. Such hierarchical structures will be peculiar to technological and running data, with a difference in the number of hierarchy levels in the key used. So for an array of cutting tools hierarchical key will include three levels of identification: type (turning, milling, drilling, etc.); part-type (feed cutter, end mill, four-groove drill); and size (cross-section of the holder, the size of the shank, etc.)
4.2. Procedures potential and target information array formation

When generating potential information in the process of rational selection and forecasting, it is necessary to begin with the analysis of the target tree in order to form the main directions for collecting information. As was shown above, such a formation is associated with the directions of improvement of technological systems. The minimum data set should characterize, firstly, the essential characteristics for which the forecast is carried out, and secondly, it should ensure the solution of the maximum number of tasks. For example, in the array of materials should be information about the name, grade, heat resistance, method of shaping (casting, deformable), the machinability and other information.

The target data set is formed at the pre-project stage and developed together with the design object according to the stages of the life cycle. This array includes:

- library of object models and design process. These include patent and (or) expert data on the components of technological systems, new manufacturing technology;
- a library of crucial forecasting procedures built on a modular principle and ensuring the construction and mutual agreement of forecasting decisions at all stages of the life cycle. The library includes tools for analyzing and evaluating prospective patents (General Definitive Table (GDT) [87]), etc.

The mechanism for creating target information systems will consist in generating and evaluating innovation flows, identifying the structure of interrelations between flows, forecasting selected components and determining source data. The structure of engineering design flows will be determined by the nature of the project problem being solved and the main development trends of the objects under consideration. The main streams of innovation include sets of promising layouts of metal-cutting machines, kinematic diagrams of new equipment designs and equipment for lubrication and transportation systems, etc.
At the stage of analysis, ranking and selection of promising generated innovation flows, a qualitative and quantitative assessment of the technical state is carried out and the level of development of the innovations in question is established. Depending on the level of elaboration (technical strategy, patent, draft and technical projects, prototype), the order of updating is established, that is, input from libraries into the system-solving procedure. Identification of the structure of the relationship between the selected flows of innovation and their components is carried out by forming chains: “the object of design – options design and technological implementations”. Accounting for previously identified rank of prospects allows you to provide a procedure for synchronizing the introduced of new design and technological data to the input of predictive procedures. However, before introducing a multitude of innovation flows into the design contour, it is necessary to predict the consequences of making promising design decisions. To obtain such estimates, the initial data and constraints are additional definition using the prediction apparatus.

One of the main prognostic components of the target information system will be a library of patent data. The structure of such a library is determined on the basis of the targets tree in the area under study. So for the purpose of the tree “Improving the accuracy and quality of technological systems”, such components will be the construction of spindle nodes with various versions of the used supports: duplex, triplex and multiplex type; cooling and lubrication systems; fixture designs - auxiliary tool system for CNC machines, various options for tool blocks, etc. For each of these components, arrays of patent data of a certain form are created — indenture arrays, by means of which a specific patent document and descriptions containing the basic information required in the design process at the initial stages are identified. The indenture array represents a hierarchical data structure with a four-level key, the components of which are headings of designations according to the International Patent Classification of inventions (IPC). The structure of
such a table (Table 4.1) for the analysis and evaluation of the lubrication system and cooling of spindle nodes is:

Table 4.1

<table>
<thead>
<tr>
<th>Class</th>
<th>Subclass</th>
<th>Group</th>
<th>Subgroup</th>
<th>Address part</th>
<th>Patent number</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>B23</td>
<td>B23Q</td>
<td>B23Q11/00</td>
<td>B23Q11/00</td>
<td>2-5545</td>
<td>2.02.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B23Q11/14</td>
<td>3-4343</td>
<td>22.01.91</td>
<td></td>
</tr>
</tbody>
</table>

An array of descriptions includes a set of information about the class of the designed object and the problem under consideration. Moreover, in its preparation should take into account information from various stages of design. This array presents data on the design schemes of spindle nodes (stage of the technical proposal); types of bearings, series of bearings, type of connection (stage of conceptual design); the preload design, the magnitude of the preload force (the stage of the technical design). Each of the listed data takes a number of values, identified on the basis of the patent fund analysis and systematized in the corresponding tables. So for the characteristics of the type of duplex-bearing connections in the support are characterized by the following options:
- duplex-O, characterized by the ability to withstand radial and axial loads separately and simultaneously in the reverse mode;
- duplex-X, which, in contrast to the previous one, is characterized by a lower overturning moment value;
- duplex-T, characterized by the possibility the use of reduced values preload with equal loads and speeds, or the possibility of increasing the maximum speed under the same loads. In addition, this connection allows you to increase axial unidirectional load and apply a spring design preload.

In order to form such arrays, it is necessary at the stage of collecting patent data to use the GDT as a means of systematization and evaluation. The maintenance of the design work will be carried out according to the
in-system search instructions in the IPC indices. The desired index will be determined by the specifics of the problem being solved. As a result of the search process, a set of patents (the address part) is selected and formed in the indenture array. These addresses are used to extract the necessary details from the table of patent descriptions. Identification of such details is made depending on the design stage, which must be specified in the search prescription. In the same mode can be carried out the process of definition extension design procedures using arrays of patent technological data. The combined use of indenture and descriptions arrays is quite an effective means of informing the process of designing technological systems for machining, along with the analysis of trends in time series and various types of individual and collective expert appraisal.

4.3. Development of a predictive database logic

Orientation of information support to the design processes of complex machining technological systems associated with a certain level redundancy design data, difficulties updating, entering new and destroying old data items. To ensure minimal redundancy and efficient data management, it is necessary to use the database design unit (DB), as a set of instances of records various types and relationships between records and data elements. The logical scheme of the database includes data of the potential and target information systems (except for decision procedures) and consists of subschemes generated by end users – designers, technologists, and operators. The procedure for constructing a logical database schema includes:
- representation of user data in the kind of normal forms [85];
- formation of canonical structures of records and canonical subschemes of data;
- merging individual subcircuits into a single canonical DB schema.
The normalization process consists of representing data elements that describe both objects and the relationships between them, in the form of tables. At the same time, the theory of normalization is based on the fact that such normalized relations have better properties when switching on, modifying, and deleting data than all other sets of relations, by means of which the same data can be represented. The non-normalized data model includes entries as used by application programs.

4.3.1. Normalization of data structures

The first step of normalization is to form a two-dimensional table containing data elements in which duplicate groups would be excluded. So, if the set of records characterizing the cutting tool includes information about the type and name and grades of cutting materials that can be used in its manufacture, then normalized ratio is a table consisting of \( n \) rows. Each line contains the type of tool and the name of one of the grades of material.

The second step of normalization is to select the keys and attributes that depend on them. Each non-key attribute of a relation tuple that is in the first normal form depends entirely on the pooled data (not necessarily all) of key attributes, that is, there is a functional relationship between them. In order to bring the relation to the second normal form, it is necessary to select groups of attributes depending on the parts of the composite (concatenated) key. These groups can form separate relationships (tables). Isolation from relations that are in the first normal form, such relations in which non-key attributes depend only on the key as a whole is the essence of the reduction to the second normal form.

At the third step of normalization, it is necessary to distinguish from the relations that are in the second normal form, those attributes that, although they depend on the key of the relations, can be identified by one or several other non-key attributes, that is, transitive functional dependencies exist in these relations.
Bringing relationships to the first, second, and third normal forms consistently eliminates various anomalies when converting records from the corresponding database. The normalization process allows the designer to more deeply understand the semantics of attributes and their interrelations and streamlines the conduct of data analysis.

In the process of reducing arbitrary data structures and the relationships between them to the form of two-dimensional tables (the basis of normalization), it is necessary to know and operate on the properties that the tables have:

1. Each table element represents one data element, and repeating groups are missing.
2. All the columns of the table are homogeneous, i.e. the elements of the column are of the same nature.
3. Columns uniquely assigned numbers.
4. There are no identical rows in the table.
5. In operations with such a table, its rows and columns can be viewed in any order irrespective of their informational content and meaning.

4.3.2. Normalization of arbitrary data structures

At the first stage of normalization (1st normal form), the greatest difficulty is the assertion about the possibility of representing any file as two-dimensional.

Task 1. We construct the file “Order for the purchase of a tool”, which is two-dimensional everywhere, except for the repeating group. It can be normalized to a two-dimensional file (figure 4.1). Thus obtained new file (table) is assigned its own name. The new file must have keys that uniquely identify any record (tuple). Item NUMBER-ORDER repeated in the file PARTY-TOOLS and together with the NUMBER-TOOLS data element form a unique identifier of the tuple.

Analysis of figure 4.1 shows the data redundancy that has appeared, but it refers only to the logical representation of data structures and does
not entail additional memory costs in the physical presentation of information. Each of the presented tuples has a key-identifier, which can be the value of one or several attributes; for the tuple of the ORDER-ON-PURCHASE-TOOL key the attribute is NUMBER-ORDERS, and for the file PARTY-TOOLS two attributes NUMBER-ORDERS and NUMBER-TOOLS (concatenated key). In this case, the key must have two properties:

- unique identification of the tuple, while the latter must be uniquely determined by the key value;
- lack of redundancy, which lies in the fact that no attribute can be removed from the key without violating the unique identification properties.

Fig. 4.1. Normalization of an arbitrary file
If there are several sets of attributes in tuples of the same relation satisfying the two given properties, then such sets are possible keys; that key which will actually be used to identify records, is the primary key. When choosing it, you should strive to reduce the number of attributes in the key. Another equivalent form of representing data in the form of relationships is a tuple of table column identifiers. So, files ORDER-ON-PURCHASE and PARTY-TOOL can be represented as follows:

ORDER-ON-PURCHASE (NUMBER-ORDER, NUMBER-SUPPLIER, DATE-ORDER, DATE-DELIVERY, TOTAL);
PARTY-TOOLS (NUMBER-ORDER, NUMBER-TOOL, TYPE-TOOL, PRICE, QUANTITY).

Before parentheses, the name of the relationship, and the names of the domains (columns of tables) are listed inside the brackets; underlined keys are required to identify tuples.

Normalization of tree data structures. To transform tree structures into a normalized form, it is first necessary to eliminate the dependencies between the vertices of the structure graph (access path) by adding new key data elements, which are usually underlined.

Task 2. Construct a normalized file “Manufacturing technology” based on the corresponding three-level hierarchical tree (figure 4.2).

The normalized form of the database schema will be represented as a tuple of identifiers of table columns.

ROUTE (NUMBER-ROUTE, KIND-MACHINING, TYPE-DETAILS, PROGRAM-ISSUE);
OPERATION (CODE-OPERATIONS, NAME-OPERATIONS, CONTENT-OPERATIONS, NUMBER-ROUTE);
DETAIL (NAME-DETAILS, CLASS-OKP, MATERIAL-DETAILS, KIND-WORKPIECE);
MACHINE (CODE-OPERATIONS, CODE-MACHINE, NAME-MACHINE);
WORK (CODE-OPERATIONS; CODE OF PROFESSION, RANK-JOBS, UNIT-STANDARTIZATION);
NORM (CODE-OPERATIONS, CODE-TYPE-NORMS, PREPORATORY-TIME, TIME-PER-PIECE);
SCALE (CODE-OPERATIONS, NAME-DETAILS);

The main operation of normalization with this data structure is the elimination of access paths. Such elimination from the tuple OPERATION to MACHINE, JOB and NORMA tuples is implemented by entering the CODE-OPERATION data element into each of the underlying tuples. The path from the tuple OPERATION to the tuple ROUTE can also to be eliminated, since in the tuple OPERATION it is
possible to include the attribute data item NUMBER-ROUTE. Each of the listed relations can have its own key (relation DETAIL) or concatenated, including a record key, standing in the tree above it (CODE-OPERATIONS + CODE-EQUIPMENT in the machine tool tuple). The introduction of additional keys in the tree structure reduces the dependence on the path (in figure 4.2, relations MACHINE, LABOUR, BASIS can be excluded from consideration). When the structure is normalized, additional data elements should be entered for two reasons. First, elements of the primary key can be added to make the concatenated key a unique identifier of the tuple, and second, attribute data elements for representing paths in a tree structure. Another method of normalization is associated with the affix of additional links in the tree structure. This refers to the type M:M relationship (many to many) between the OPERATION and DETAIL relationships. One part can be machined using various technological operations and one operation can be applied to machining various parts. If we add the item NAME-DETAILS to the tuple OPERATION, then we would have to repeat the tuple several times for one technological operation. This duplication is inefficient; more rational creation of a new tuple consisting only of the data elements CODE-OPERATIONS and NAME-DETAILS. This allows you to find the part that are processed using this operation and all technological operations used to process this part.

4.3.3. Normalization of network data structures

For complex network structures, when at least one of the communication lines of the scheme will have double arrows in both directions (type M:M), you should create an auxiliary record or segment with a concatenated key.

Task 3. Elimination of type M:M communication. Consider two records of MACHINE and RETAINING DEVICE (figure.4.3)
Several clamping devices can be installed on one machine and at the same time one device can be mounted on several machines. This statement corresponds to the existence of a M:M bond between them. You can eliminate this unwanted link by entering a new SCALE entry (figure 4.4):

A characteristic feature of network structures is the presence of intersection data, that is, data bind (associated) with a set of records (as opposed to a tree structure).
**Task 4.** Elimination of type M:M communication in the presence of these intersections. In the network structure of a complex of products, a part can be entry into node and directly into a workpiece (figure 4.5).

![Diagram of relations WORKPIECE, NODE, and DETAIL]

Fig. 4.5. Elimination of relation type M:M

The presented set of relations WORKPIECE, NODE and DETAIL has better properties for inclusion, modification and deletion of data than all other relations, with the help of which such data on engineering products and their accessories can be presented. This diagram shows the data domains (columns of two-dimensional tables), which are filled with specific information about the products, a set of nodes and a different nomenclature of machine tool construction parts.

The data item QUANTITY-DETAILS is associated with both the entry WORKPIECE and the entry NODE. To eliminate M:M type links, when the intersection data is available, it is necessary to enter three new records identified by the corresponding keys. WORKPIECE NUMBER+NODE NUMBER, WORKPIECE NUMBER + DETAIL NUMBER and NODE NUMBER+DETAIL NUMBER. These keys uniquely identify the corresponding tuples WORKPIECE, NODES and DETAIL. At the same time, there is no redundancy of information and none of these attributes can be removed from the key without violating the unique identification properties (figure 4.6).
Certain complexity is the normalization of network data when file records are associated with other records of the same file by a "loop" link. If we consider the database of the product complex, then in the node file some nodes may themselves consist of nodes. Then, depending on the nature of the problem being solved, the loop-like connection may be of the type M:M of the type 1: M.

**Task 5.** Elimination of the loopback link in the NODE file. Loop type M:M in the node file is eliminated by entering an additional record (segment) which identifies the relationship between nodes at different levels of the hierarchy. When analyzing various forms of information presentation and selection for use, it is necessary to take into account that the main advantages of a normalized form are simplicity and consistency.
**Task 6.** Making changes to the design documentation. Consider the scheme of the file, representing the 6–level structure of the workpiece, consisting of nodes of different hierarchy levels and details. The normalized form of the file contains two relationships:

1) WORKPIECE (unit, design), including information about the attributes of the NUMBER-WORKPIECE and NAME and another attribute CATEGORY, indicating whether the entry relates to the finished product or a node of one of four levels;
2) EXPLOSION, which reflects the number of nodes (details) of each type directly included in this workpiece.

Information about the structure of the workpiece must be stored both before and after making design changes to the product. The operation of making changes is much easier for the file normalized presentation than for a file represented as a network structure. In this case, for each design product, a new relationship is formed – CHANGE (NUMBER-CHANGES, NUMBER-WORKPIECE) and is added to the previously formed relations WORKPIECE and EXPLOSION.

### 4.4. Manipulating by normalized relationship

The flexibility of the information database is determined by the ease with which relations can be manipulated with the help of the apparatus of relational algebra (the algebra of interrelations between specific sets – relations). The use of this device will be considered on the example of drawing up a DISTRIBUTION-ORDER relationship with an indication of a specific drawing of a detail machined on a Thread-Cutting Lathe (TCL) 16K20F3 from a machine relation (figure 4.8).
1. In the first stage, combine the three relationships into one. To do this, one line of the relationship can be considered as an element of the set and take a direct multiplication of the three relations. The direct multiplication ($\otimes$) $D_1, D_2, ..., D_n$ sets is understood to be a set consisting of tuples $<d_1, d_1, ..., d_n>$ each of which consists of consecutive elements $d \in D_i (i = 1, 2, ..., n)$, taken one from each set. The join operation is written as follows:

DISTRIBUTION-ORDERS $\otimes$ COMPOSITION- WORKPIECE $\otimes$ MACHINE
2. Having performed a direct multiplication, we obtain a large MACHINE LOADING (Table 4.1) ratio, from which it is necessary to extract only the necessary data.

In the first extraction step, only those rows are fixed in which the detail type from the relation DISTRIBUTION-ORDERS and the type of detail from the relationship COMPOSITION- WORKPIECE are identical. To identify identity, it is necessary to use the extraction operation, written as follows:

\[
\text{LOADING-EQUIPMENT} \{3 = 5\},
\]

where 3 and 5 are attribute numbers in relation to LOADING-EQUIPMENT corresponding to the type of detail in the distribution DISTRIBUTION-ORDER and COMPOSITION- WORKPIECE.

In the second extraction step, only the rows corresponding to the 16K20F3 machine model are of interest, which is written as follows:

\[
\text{LOADING EQUIPMENT}'' = \text{LOADING EQUIPMENT}' \{2 = 9\}.
\]

Here the indices " and ' mean the modification of the initial relation obtained as a result of the execution of the operators, respectively, \(\{2 = 9\} (''\) and \(\{3 = 5\} (')\). If you need only data about the details processed on this machine, you should apply the operation of selecting the required column, which in relational algebra is called a projection. For our drawing details (attribute number 6) we write in the form: LOADING-EQUIPMENT \{6\}. The result is the right answer.

The presented sequence of operations can be written as a single expression:

\[
(DISTRIBUTION-ORDER \otimes COMPOSITION-WORKPIECE \otimes MACHINE) \{3 = 5\} \{2 = 9\} \{6\}.
\]

In the above transformations, the operations of direct multiplication, constraints (highlighting lines satisfying specified conditions) and projections (highlighting the required machine) are presented. With these constraints, relationships are exploring
by horizontally and vertically. Along with these three operations, information support uses five operations of relational algebra: *division*, *union*, *intersection*, *difference*, *conjunction*.

**Division.** Consider the relations $R(x, y)$ and $S(z)$ which are effectively defined through the category “direct multiplication” as a subset of tuples of a direct multiplication $<x_1, x_2, ..., x_n>$ that make up the relations of the subject area and for which the statement $P(x_1, x_2, ..., x_n)$ is true. Here $P$ – predicate expressing the fact that a tuple satisfies a relation that is valid in a given subject area.

The division $R\{y \div z\}S$ is an operation defining the largest attribute set $x$ such that the direct multiplication of this set with $S(z)$ is contained in $R$, i.e. for all $S$ elements of the relation $S(z)$ division is the operation of determining such a set of components of the tuple $r\{x\}$ ($r$ – a tuple is an element of the relation $R$) corresponding to a subset of $x$ values such that $(r\{x\}, S)$ is contained in $R$. When forming a relationship LOADING - EQUIPMENT the result of the division is $r\{x\} = (1, 2, 3, 4)$ such that $\{(1, 2, 3, 4), 9\} \in R(x, y)$, where 1, 2, 3, 4, 9 – serial numbers of attributes used as their names.

**Union.** This is the operation of obtaining the relation of a fully unifying tuples, contained in the relations $R(x, y)$. The resulting relationship, by analogy with the usual operations on sets of operations, is called the “set-sum” $R \cup S$:

$$ R \cup S = \{x | x \in R \lor x \in S \} \quad \{1, 2, 3, 4, 5, 6, 7, 8\} \quad \{9\} $$

where $\lor$ and $\land$ – logical addition (disjunction) for sets and elements of sets.

**Intersection** – the operation of obtaining a relationship, consisting of common tuples of relations $R$ and $S$, or by analogy with sets – obtaining a common set $R \cap S$:

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\( R \cap S = \{ x \mid x \in R \land x \in S \} \)
\( \{1, 2, 3, 4, 5, 6, 7, 8\} \)
\( \{9\} \)

where \( \cap, \land \) – logical multiplication (conjunction).

*Difference* is the operation of obtaining a relation consisting of tuples that are tuples of a relationship \( R \) and non-tuples of a relationship \( S \)

\( R - S = \{ x \mid x \in R \lor x \notin S \} = \{1, 3, 4, 5, 6, 7, 8\} \).

*Conjunction* is the most important operation, which is the inverse of a projection. The combination of two relations \( R(x, y) \propto S(y, z) \) is understood as an operation using the common attribute as a feature of a conjunction. As a result, get a new attitude:

\( R \propto S = \{ x, y, z \mid (x, y) \in R \land (y, z) \in S \} \).

Consider using the conjunction operation when forming the resulting relation TASK-ON-DESIGN based on two relations DESIGNER and ORDER (figure 4.3). A common attribute and a sign of the connection is the PERSONAL-NUMBER of designer. It should be noted that only in case of coincidence of attributes PERSONAL-NUMBER in relation to ORDER and PERSONAL-NUMBER in relation to DESIGNER it is possible to receive a new line (tuple) in the resulting relation. Such a strict requirement (complete coincidence of attributes) limits the scope of application of the classical Ulman conjunction operation. To expand connectivity, you can use modifications of the conjunction operation: \( \Theta \)-conjunction, equicon conjunction, semi- conjunction, external conjunction.

\( \Theta \)-conjunction used when forming the resulting relation, when it is possible to compare the attribute \( x \) of the relation \( R \) and the attribute \( y \) of
the relation S, and the names of these attributes do not necessarily coincide.

The resulting ratio (figure 4.9) presents the attributes x and y:

$$R\{(x \Theta y)\}S = \{(r, s) | r \in R \land s \in S \land r\{x\} \Theta s\{y\}\}$$

Equicon conjunction is used when \(\Theta\) is an equal sign: \(R \{x = x\}S\); at the same time, the resulting relation attributes with the same content occur once. Hence, the connection \(R \propto S\) by the general attribute x is equivalent to the operation of equicon conjunction of two relations \(R \{x = x\}S\). Here x to the left of the equal sign means an attribute x in R-relation, and to the right of an equal sign an attribute y in S-relation. If there are no common attributes, then \(R \propto S\) is by definition equivalent to the direct multiplication of R and S.

![Diagram of relation and operation](image)

Fig. 4.9. Implementation of the operation “Conjunction”
A semi-conjunction is a $\Theta$-conjunction operation in which all the attributes of one of the joined relations are excluded from the result. It is denoted by $R < x \Theta y \} S$:

$$R < x \Theta y \} S = \{r / r \in R \wedge s \in S \wedge (r \{x\} \Theta s \{y\})\}.$$

In this operation, from relation $S$, you first get a projection on the attribute $y$ (in figure 4.4 before forming the relationship DESIGNER $\propto$ ORDER, you can get the relationship LIST-DESIGNERS who participated in the design of a similar workpiece in the current month), and then carry out the operation restrictions for the relationship $R$ (ORDER).

*External conjunction.* This operation is typical for the case when some values of the corresponding attribute are unknown, and the connection is interpreted positively. For an example of the formation of the resulting TASK-TO-STRUCTURE relation (figure 4.4) with an external connection, when there are personal numbers for the relation CONSTRUCTOR that are missing for the relation ORDER (that is, for the ORDER, no task is provided for issuing a task to a certain constructor). In this case, the following attributes are written to the resulting relation: ACCOUNT NUMBER, WORKPIECE TYPE, and QUANTITY - with valid input of empty attribute values PERSONAL-NUMBER.

*Reduction to the third normal form.* Consider the fragment of the database DESIGNER. A set of relations in the 1st normal form: DESIGNING, METHOD-DESIGN, DESIGNER, etc. Let's bring to the 2nd normal form. So for the relationship DESIGNER this procedure can be represented in the form of the following diagram. Analysis of the dependencies between the attributes of records shows that the attribute PERSONAL-NUMBER is not functionally dependent on the attribute BASIC-RATE, since several designers can have the same salary. Similar to PERSONAL-NUMBER is not functionally dependent on the
DRAWING-NUMBER attribute. Attribute ENDING-DATE, on the contrary, has such a relationship (figure 4.10).

Primary attributes are marked with an asterisk in the diagram, i.e. attributes included in one of the possible keys. This ratio is not a relation in the 2nd normal form, since the attributes BASIC RATE, ENDING-DATE and COST-OF-DESIGNING without being primary, functionally depend on attributes PERSONAL-NUMBER, DRAWING-NUMBER and COST-OF-DESIGNING respectively. The various combinations of communication are subsets of a composite (concatenated) key. To bring the 2nd normal form, “split” the original relation into two parts (figure 4.11).

Fig. 4.10. Reduction to second normal form
In the first of the selected relations there is a transitive dependence, consisting in that the attribute COST-OF-DESIGNING depends on the attribute ENDING-DATE, which in turn depends on attribute DRAWING-NUMBER. This relation can be reduced to the 3rd normal form by splitting it (figure 4.12).

Fig. 4.12. Reduction to the third normal form
Similarly, the reduction to the 3rd normal form of relations is carried out – METHOD-MANUFACTURING, EQUIPMENT and CUTTING- TOOL. On the basis of these normalized relations, the construction of a logical DB schema is carried out.

Along with the above-described operations of combining data elements in a record (segments), there are special techniques for synthesizing groups of data elements into a DB scheme according to Jef. Ullman, consisting in minimizing data structures called canonical. This procedure is implemented by successive addition to the basic structure of relations in the 3rd normal form. At the same time, the ability to delete some simple links, the formation of concatenated keys, etc. is evaluated.

4.5. Building a database schema
“Technological system

Consider the design features canonical scheme on the example of a fragment of the database “TECHNOLOGICAL SYSTEM” (figure 4.13). First of all, it is necessary to remove traversing attributes (attributes that are connected by arrows with several keys). So attribute 9 is intersecting (connections 1 ⇒ 9 and 8 ⇒ 9). Removing the 1 ⇒ 9 link is carried out by introducing an additional link between the corresponding keys 1 ⇒ 8. But in this case, this link is implemented with the concatenated key 1 + 8, in which key 1 is included as a component. The presence of type M: M connection between the keys MODEL-EQUIPMENT ⇔ METHOD MANUFACTURING makes it necessary to enter an additional concatenated key (8 + 10). Similar connections 10⇔14 and 10⇔20 are eliminated similarly by entering concatenated keys (10 + 14) and (10 + 20). In an equivalent way, this logic can be represented in the following normal form, by eliminating dependencies on access paths by adding new key elements (indicated by a double bar).
METHOD-MANUFACTURING \{NAME-METHOD, INFORMATION-ABOUT-METHOD\);

EQUIPMENT (METHOD-MANUFACTURING, MODEL-EQUIPMENT, PASSPORT-DATA, PATENT-DATA, YEAR-CONSTRUCTION);

RETAINING-DEVICE (MODEL-EQUIPMENT, NAME – RETAINING-DEVICE, PASSPORT-DATA, YEAR-DESIGN, PATENT-DATA);

CUTTING-TOOL (MODEL-EQUIPMENT, CODE-TECHNOLOGICAL-TRANSITION, NAME-CUTTING-TOOL PATENT-NUMBER, DATE-PATENTS, MATERIAL-CUTTING-PARTS, GEOMETRY-CUTTING-PARTS, FORM-CUTTING-PLATES, CONSTRUCTION-FASTENINGS, DEVICE-FOR-CHIP-BREAKING, TYPE-CUTTING-EMULSION);


DESIGNER (NAME-DESIGNER, INFORMATION-ABOUT-DESIGNER).

Connection of various DB fragments “TECHNOLOGICAL SYSTEM” is also connected with methods of normalizing relations, including the method of eliminating overlapping attributes (for example, MODEL-EQUIPMENT ⇒ INFORMATION-ABOUT-DETAILS) by introducing new connections between the corresponding keys (MODEL-EQUIPMENT ⇒ DRAWING-NUMBER-DETAILS + WORKPIECE-NUMBER), which in the case of application of group technology are of type M:M (for a single technology, the type of connection is 1:M). The presence of a M:M connection (for example, MODEL-EQUIPMENT ⇒ METHOD-MANUFACTURING in figure 4.13) makes it necessary to enter an additional linked key (METHOD-MANUFACTURING+MODEL-EQUIPMENT)
Fig. 4.13. The logical scheme of the database "Technological system":
ND – number of drawing details; DPN – designer's personnel number; ED – end date; PC – project cost; MM – manufacturing method; MD – manufacturing method data; BR – basic rate; RD – name of retaining device; PD – passport data; DY – the year of design; PD* – patent data; DN – name of the designer; NP – name of the manufacturing step; TI – information about the manufacturing
step; CTN – the name of the cutting tool; PN – patent number; PDa – the date of patenting; CPM – material of the cutting part; MD – mounting design; CB – method of chip breaking

As a result of performing all the above procedures, a logical scheme of the database “TECHNOLOGICAL SYSTEM” is formed, ensuring their minimum redundancy and independence from the application programs using this data.
CONCLUSION

1. For the first time, a methodology and a toolkit for a rational choice of design decisions based on the idea of parallel design of five components: a set of design alternatives, a declarative and procedural model, a system of priorities and a choice result were developed. A feature of this approach is the embedding into the selection process contour of forecasting and optimization procedures. Entering a procedural model allows you to concentrate information on possible trends in the development of the objects in question and specific promising designs of technological machining systems.

2. To substantiate the rational choice, a set of postulates has been proposed, the implementation of which makes it possible to judge the rationality of the design decisions made. These postulates regulate the composition and specificity of information that provide an effective assessment of alternatives in accordance with the criteria that are included in the system of preferences. They are also used to implement the project operators contained in the procedural model, taking into account the description of the consequences of the actions of these operators.

3. The monograph draws attention to the aspect of completeness of actions necessary for such modernization of technological systems, which takes into account various performance criteria belonging to the component “System of preferences”.

4. Two principles are introduced and interpreted, on which the rational choice scheme is formed. The first is associated with the minimum dimension of the alternatives description and predetermined by the problem of reducing constructive properties and parameters of designed objects. The second principle reflects the situation when the
“Result of choice” component contains all the necessary data within the scope of the subject area to which the projected system belongs. The main conclusion of the proposed apparatus is the statement: “If the technology of parallel design for technological systems proposed in the monograph meets the above basic principles and postulates then it can be argued about rational (quasioptimal) version of the projected research object”

5. A toolkit for updating objects of a rational choice modified scheme, which provides a procedure for forming a component of the “Declarative TS Model” scheme has been developed. This allows you to give a complete, workable understanding of the design object. A feature of this representation is the embedding of patent and expert search procedures at the initial stages of the object creation, in terms of physical effects and principles of operation. In this case, the designer has the opportunity to distinguish between fragments of a complex TS, which should to be modified as a result of a change in value concepts from fragments, which remain unchanged. This contributes to the implementation of a competitive general technical scheme and the layout of the designed technological system.

6. A method for constructing a target tree and the corresponding regulated procedures for the system account of development and improvement trends are proposed. This allows, on the basis of “Procedural knowledge”, both to directionally select mutable and immutable fragments of the projected TS, as well as to identify the links between these two representation.

7. Based on the developed rational algorithm a promising design of high-speed spindle node supports for multi-functional machine model SF68VF4 (CNC milling and boring machine) are proposed. In this case, a comprehensive account of the various selection criteria in the form of a 9-stage procedure for the formation of project alternatives was taken. In this case the generation of alternatives is practically no need to use quantitative estimates. A feature of this procedure is to take into account forbidden combinations (for
example, installation of “duplex-tandem” type supports from various bearings, etc.) It is proposed to determine such forbidden combinations by interacting two components of a rational choice scheme: “Spindle node options” - “System of preferences”.

8. The methods and models of geometric programming were introduced into the practice of rational choice. They are most complete reflect the engineering essence of the problem, provide an assessment of the components significance by optimization model, and effectively use the capabilities of a computer. For the problems of geometric programming of the difficulty first degree, embedded in the mechanism of rational choice, a procedure that involves the integration of several optimization methods in a single circuit for solving design problems has been proposed. Using the example of the three-parameter problem of cutting conditions optimization, we show the advantage of the express procedure for calculating the lower boundary of the objective function with varying values of the desired variables.

9. The search for optimal values of the modes for one- and two-pass machining by milling, drilling and boring are realized. A comparative evaluation of the various procedures effectiveness for optimizing the characteristics of technological systems has been carried out.
REFERENCES


13. Kaminsky V.V. Optimization of parameters of the bearing system of rotary machines / Machines and tools, 1984, is. 10. – P. 12–16.


[https://doi.org/10.1088/1742-6596/1084/1/012007](https://doi.org/10.1088/1742-6596/1084/1/012007)


[https://doi.org/10.7546/pmmtd.2018](https://doi.org/10.7546/pmmtd.2018)


[https://doi.org/10.1016/j.proeng.2017.10.581](https://doi.org/10.1016/j.proeng.2017.10.581)
32. Averchenkov V.I. Multi-criteria optimization of machining modes according to parameters V. 8 / Izvestiya Vuzov. Mechanical Engineering – Moscow: Moscow Technical University, 1984, is. 4. – P. 143–146.


https://doi.org/10.15587/1729-4061.2018.131778


https://doi.org/10.1007/978-3-319-93587-4_38


44. Senkin E.I., Kolyadin A.V. The choice of effective designs and working conditions of stepped mills // Machines and tools, 1984. – is. 11. – P. 21–22.


72. Levina Z.M. Calculation of the rigidity of modern spindle bearings / Machines and tools, 1982, is. 10. – P. 1–3.

73. Lizogub V.A. Designing and calculation of spindle assemblies on rolling bearings / Machines and tools, 1980, is. 3. – P. 18–20.


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84. Krol O.S., Krol A.A., Evtushenko S.V. Designing prismatic shaped cutters using parametric modeling in the ARM GRAPH environment/ Collection of scientific papers. – Lugansk: Publishing
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