CHAPTER 2. CREATION OF THE PRODUCT

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Creation of competitive machine-building products is a system of tasks of hierarchical structure: research, design, engineering, technological, economic and production, connected by direct and feedback connections in space and time.

Rational organization of the production process is impossible without its careful preparation.

The work of creating a product is performed during research and design preparation of production.

Research preparation of production − part of the preparation of production, which consists in conducting applied research in order to verify the correctness of new technical solutions to improve products, equipment, technology, composition of materials used, organization of production and management.

As a component of system technology, research preparation of production includes the following tasks:

– approximate assessment of the technical feasibility of the idea;

– studying the possibility of using new design solutions, new materials, technologies;

– forecast of the volume of demand for future products and its development;

– specification of the technical task for product development (modernization);

– clarification of many conditions and functions performed;

– development of an enlarged product model;

– analysis of production and sales opportunities;

– analysis of the planned control indicators of sales, costs and profits in order to establish compliance of the product design and marketing strategy with the objectives of the enterprise;

– determining consumer requirements for a new product;

– determining the location of a new product relative to those that already have market recognition;

– determining the possibility of creating incentives for potential buyers to purchase a new product;

– identification and solution of possible legal problems (patent situation).

The result of the stage: the decision on the feasibility of creating and producing a new product. The closer the new product is to the products of the existing range, the less the need for research.

Construction − the process of creating a specific, unique structure of an object. The construction is based on the design results and clarifies all engineering decisions made in the design.

Design as a component of system technology includes:

– design of products and other systems aimed to meet the needs of the external environment of their operation;

– comparison with the help of preliminary samples, prototypes, computer and other models of different alternatives for building or improving a product and choosing one of them;

– development and coordination of design and engineering documentation intended for mastering in production or for improvement of the existing system at any of the stages of its LC.

The result of the design is a project of practical creation or improvement of the system at the stages of its LC.

The product design process must be systematic and have four levels of hierarchy: the level of the system that will include the product as its element (supersystem, product environment), the product level, the level of assembly units and the level of product parts.

In the first case, the interaction of the developed product with its external environment is considered. This design of the object is called **external**, and its results are a set of functional characteristics necessary to achieve the goals of the system in which the developed object is included as an element.

In the second case, the developed object is considered as a system of elements. Both the elements themselves and the connections between them are considered. This design of the object is called **internal**.

Tasks of internal design are subordinated to the task of external design and consist in the definition of such principle of action, structure and set of values of parameters of the object at which functional characteristics of the developed object are not lower than the set ones.

Based on this, the design of the machine is divided into functional design, which forms the principle of its operation and technical design, according to which on the basis of the selected principle of functioning the design of the machine or its assembly unit, or a part is created.

The organization of design preparation of production at the enterprise can be carried out in two directions: by performing all major works related to the development of new and modernization of existing products directly at the enterprise, or by concluding a contract for technical documentation with an organization-developer and finalizing and adjusting it to conditions of the enterprise.

When designing a product, it is necessary to take into account the required level of quality, which on the one hand, should fully satisfy the consumer, and on the other hand – to ensure a fairly low cost of production and efficient use of resources available at the enterprise. This means that the design must take into account the qualifications of personnel working at the enterprise, the possibility and feasibility of using already tested raw materials, consistency of relations with reliable suppliers, as well as the fullest use of production capacity of the enterprise, of each group of its equipment.

The structure of modern machines is characterized by the transition from a structure with many parts of a simple shape to structures with fewer parts, but of more complex shapes. This reduces the number of mechanical connections between parts, increasing the number of geometric (dimensional) connections between parts and their geometric elements. Reducing the number of individual parts in the product simplifies assembly processes, while increasing the number of dimensional relationships relative to the geometric elements of the parts shifts the centre of gravity to the processing.

Any technical system (machine) is created to carry out the technological process of manufacturing a product in order to meet a need of a human, society. This need is the main stimulus for the creation of a technical system (Figure 2.1).

Needs are always a little ahead of the technical capabilities of their provision. The desire to meet needs is the engine of continuous development of science, technology and, in particular, mechanical engineering.

2.1. Development stages

Design and engineering preparation of production (DPP), as it is known, consists of a number of stages: technical task; technical proposal; sketch project; technical project; development of working documentation; making a prototype.

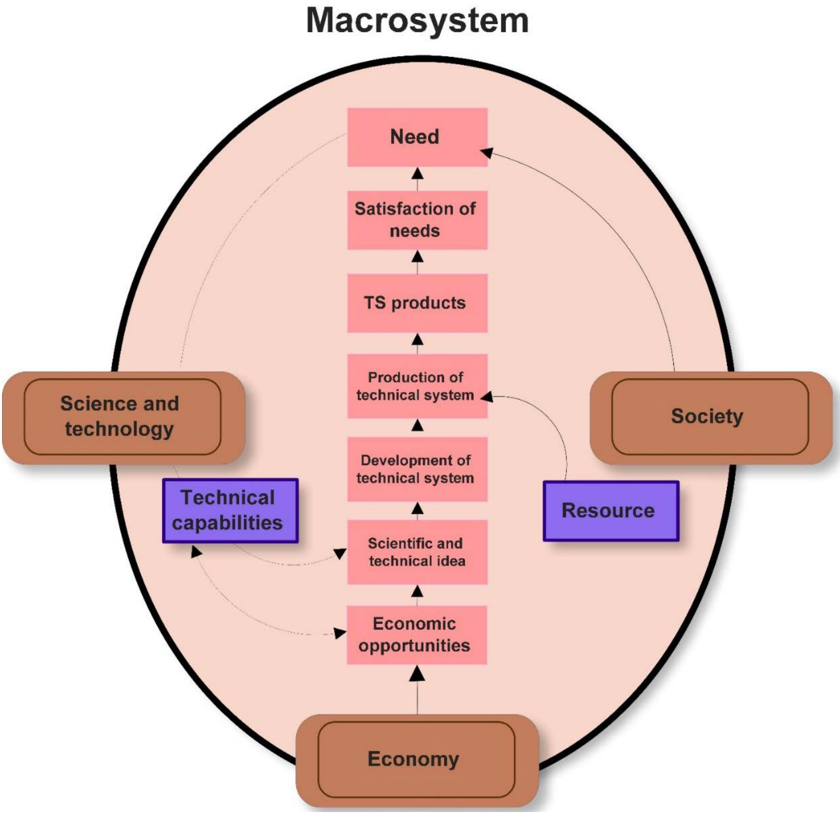

Figure 2.1 – Scheme of creating a technical system

The machine can be really useful only when it can meet the requirements of the customer. The degree of usefulness of the machine is determined by its compliance with its functional purpose.

Functional (official) purpose of the machine − the most precise and clearly defined set of functions for which the machine is designed. Preliminary service purpose of the car is formed by the customer at development of technological process of production of any production and is specified at registration of the technical task for designing of a car.

Formulation of the functional purpose of the machine with subsequent execution in the form of a technical task for design is carried out by the main developer of the machine after conducting thorough marketing research.

Since any machine is created to perform the function of manufacturing a product, in order to meet a need of a human (society), the formation of the functional purpose should begin with the study and description of this process.

A systemic approach is required when formulating the functional purpose of objects. For example, a machining station, being a system of interconnected parts and assembly units, is part of the manufacturing supersystem as an integral part; an assembly unit, being a system of parts, is included as a subsystem in the machine; a part as a system of interconnected surfaces is included as a subsystem in the assembly unit.

Therefore, when formulating the functional purpose of an assembly unit, it is necessary to formulate and clearly imagine the functional purpose of the machine, for details – the functional purpose of the assembly unit, because knowing the requirements for the system, you can develop requirements for the subsystem.

Each part of the machine is responsible for performing certain functions arising from the main function, for the implementation of which the machine is created. Together, these functions should be reflected and specified as much as possible in the functional purpose of the part. The functional purpose of the part is realized by its surfaces, which perform certain functions.

For example, the main function of the gear "Torque transmission" is realized by the ring gear and the side surfaces of the keyway of the hub. The auxiliary function of the gear wheel (base) is realized by the hole and the end face of the hub and the side surfaces of its keyway.

The formation of the functional purpose should consist of two main parts: the **general part** and **clarifications** (Figure 2.2). Formulation of the general part of the official purpose (main function) is usually not difficult.

When defining a function, first it is necessary to indicate a verb that describes the main action of the technical system (TS) and answers the question "what does it do?". For example, it fixes, processes, transports, transmits, and so on. Then the object to which this action is directed is indicated: secures the body, fixes the lever, processes the workpieces of the shafts, transports goods, etc.

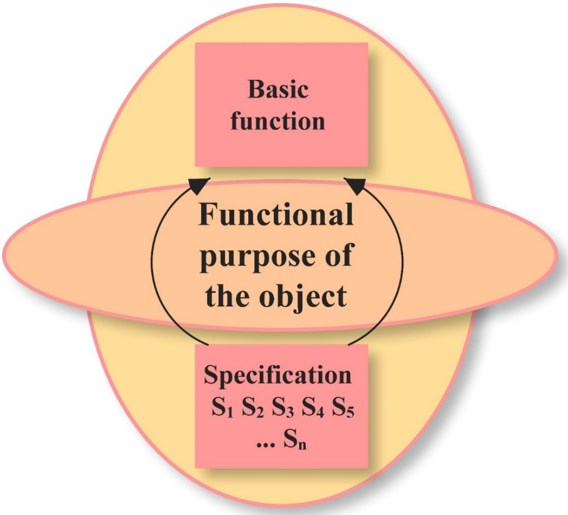

Figure 2.2 – Structure diagram of the functional purpose of an object

For example, the main function of a lathe − to process workpieces of shafts.

The general function does not reveal the specific purpose of the object, so it must be detailed (specified) by setting functional parameters that describe the specific limiting conditions for the implementation of functions (plural {Y}). In other words, it is the characteristics of the environment that determine the quality of the function. Thus, the shafts include rollers of watch movements, and shafts of gearboxes of machines and columns of heavy presses. It is impossible, and there is no need, to create such TS which could process preparations of any of these details. That is, it is necessary to specify the sizes of shafts for which processing TS is intended.

Further refinement of the functional purpose should be related to the number of workpieces to be machined. If the TS is intended for the manufacture of a wide range and a small number of parts, its design must be universal, if for the mass production of identical parts − special.

The following refinement of the functional purpose is related to the requirements for the accuracy of the parts to be manufactured: accuracy of diametrical and linear dimensions, accuracy of shape, accuracy of relative location, as well as the roughness of the treated surfaces.

It is also necessary to specify the modes under which processing should be carried out: type of workpieces, their material, processing productivity, level of process automation, conditions in which TS should work (possible fluctuations of ambient temperature, humidity and dust), etc.

In the general case, a set of functional parameters FP = $\{y_n\}$ may include:

1) composition and requirements for constructive structure;

2) comprehensive data on the product (action) that TS (machine, unit) must produce (perform), its type, parameters, quality and quantity;

3) performance indicators, economic efficiency, durability and reliability of TS (machines, units, parts);

4) a list of conditions under which the TS must operate and produce products (produce action) of the required quality in the required quantity (quality of the input product, energy supplied, mode of operation, state of the environment, etc.);

5) requirements for appearance, occupational safety, convenience and ease of maintenance and management, noise level, vibration, efficiency, degree of mechanization and automation, etc.;

6) requirements for maintenance and repair;

7) annual demand for TS and the economic effect of its use, etc.

When formulating the functional purpose of a particular object, in addition to the deepest possible refinement, it is necessary to quantify these refinements with tolerances. The set of indicators that describe the functional purpose with the tolerances set on them is a **technical condition** (TC) and **accuracy standards** for the acceptance of the finished TS (machine, unit, parts).

As you can see, the detailed formulation of the functional purpose of the object creates its original image and is an important point in the development of the technical task for the design.

For the **designer**, it is the source in the design of TS (machine, assembly, parts), for the **technologist** – in the development of manufacturing processes. The tasks to be solved with the help of TS must be clearly defined and correctly implemented.

Errors made in identifying and clarifying the functional purpose of TS (machine, assembly unit, parts) lead to the creation of low-quality objects, unnecessary labour costs for their manufacture, development and operation.

Based on the functional purpose, a technical (design) task for product development is created.

The composition of the developed product "PD" can be represented by a set of parts (P) and complex units (CU):

$$\mathrm{PD} = \left\{ \left(P + \mathrm{CU} \right)_{st} + \left(P + \mathrm{CU} \right)_{b} + \left(P + \mathrm{CU} \right)_{u} + \left(P + \mathrm{CU} \right)_{or} \right\},$$

where indices mean: st – standard; b – borrowed; u – unified; or – original.

The smaller the proportion of original parts and CU in the product, the easier it is to make. For example, companies Toyota, Nissan, Boeing, use in their products only up to 25% of the original elements.

The product and marketing strategy are tested in terms of real use of the novelty in order to clarify the views of consumers and dealers on the specifics of operation and use of the product, the problem of its resale, as well as to determine the size of the market.

At this stage, the product and marketing program operate in conditions closest to real. This work, as a rule, gives the full amount of initial information for the beginning of serial production, allows to define rather precisely the actual level of production costs, to establish the price and to define ways and methods of advancement in the market of a new product.

In addition, the state of the technical base of the enterprise, its readiness for product production is analysed. The less changes are needed to improve production, the lower the cost of developing a new product there will be, the easier and less painful to perceive it will be for the company.

Quality problems are investigated and measures are developed to ensure it in a new product. Sales professionals continue to search for potential consumers.

Market research provides management with sufficient information to make a final decision on the feasibility of a new product.

Typically, after the end of each stage of the DPP, a comprehensive analysis of the results achieved, on the basis of which it is possible to return from any stage to any previous stage with the repetition of the necessary procedures. Thus, the process is iterative and allows to achieve a fairly reliable result.

Traditional design, based on the intuition, experience and skills of the designer, is not able to provide a high-quality TS project in a short time. The main way to improve the quality of projects, reduce material costs, reduce design time and increase the productivity of designers is to use at all stages of development of computer equipment and information technology.

The main design trend is the transition from two-dimensional to three-dimensional modelling to solve problems at all stages of PLC.

In the process of DPP at the stages of technical task (TT) and the technical proposal should use specialized problem-oriented application packages that allow on the one hand to perform expert assessments of cost-effective TT parameters for a machine, taking into account the wishes of users (CAE), and on the other – to form image geometry and layout of the future TS.

With the help of geometric 3D-surface and solid-state modelling (CAD) in addition to the formation of external contours, one can determine the existing static and dynamic, concentrated and distributed loads.

At the stage of the sketch project the range of tasks is significantly expanded. This is a refinement of the geometry of components and parts with modelling and assessment of the state of the structural material (stresses, margins, service life, etc.).

At the stage of technical design, 3D modelling is used for spatial dimensional chains in order to match the tolerances of conjugate surfaces and the relative location of parts (CAD). The technological (CAM) package for development of structure of assembly units which will form a basis of development of assembly drawings and assembly technology with an estimation of a cycle of assembly and development of TT on necessary technological equipment (CAE) is connected here.

At the stage of working project with the help of geometric (CAD) flat (2D) and three-dimensional (3D) modelling, work drawings of details are developed, and with the help of technological (CAM) package – development of processing of workpieces with a full set of technological and technical-economic documentation.

The design procedure is supported by knowledge management tools, including various libraries, which reduce routine work – for example, libraries of bearings, fasteners, hydraulic elements, tolerances and landings, etc.

To prevent the launch of unreliable products during product design, periodic control, analysis and evaluation of their quality by novelty, complexity, features of production, application and technological and regulatory control of documentation is carried out. The evaluation of the project as a whole is carried out by the customer, to whom the developer provides all the necessary materials: terms of reference, draft specifications, design and other technical documentation, test results and other information confirming the technical level, competitiveness, safety and environmental friendliness of the product.

The range and content of work performed at all stages of design preparation of production may differ for each enterprise depending on the type of production, complexity of construction, the degree of its unification and other factors. For example, in the case of a single type of production, no work is carried out related to the manufacture and testing of prototypes, and a preliminary design is often combined with a technical design. But the content and essence of design preparation of production of all types of production remain the same and inevitably find their continuation in another phase of technical preparation of production.

2.2. Design of technical systems

Any object can be described as a system of functions that it and its elements perform, and as a system of structural elements.

Accordingly, there are functional and technical (geometric) structures of the object, which graphically reproduce the relationship of functions to perform the object of its functional purpose and the interconnections of structural elements of the object.

Structures can be described as a total of sets:

functional $S_{ф} = (\{F\}, \{K\})$,

where $\{F\}$ – set of functions;

$\{K\}$ – set of relations between functions:

technical $S_{ф} = (\{E\}, \{R\})$,

where $\{E\}$ – set of structural elements;

$\{R\}$ – set of geometric (dimensional) relationships between elements.

Therefore, the process of designing a technical object is divided into functional design, which forms the principle of its operation, and technical design, when on the basis of the selected principle of operation a structure of the technical object is created.

Functional design – the process of creating the principle of operation of a technical object as a system of interconnected simple functions. The design begins with the decomposition of the main service function of the object into a set of simple functions and the establishment of connections between them. The purpose is to define these functions and to choose rational types of connections.

Technical design – the process of creating a geometric image of the elements of the technical object, their interaction and geometric structure that implement the specified functions.

2.2.1. Functional design

Any material object (machine, unit, part, surface of the part) as such has no consumer value. Consumer value has a set of functions that it performs. Functions usually manifest as signs of quality indicators when using an object. Therefore, any real object is perceived as a set of its individual features.

The features that characterize an object in certain conditions are called service functions. The function answers the question: "What should the object do?". A function is the content of the elements from which a system is created.

There are main and auxiliary (secondary) functions.

The main function of an object – feature that defines its essence, purpose, for the implementation of which the object is created and without which it, as a product, loses its consumer value, usefulness.

So, the main functions of the metal-cutting machine are processing of workpieces of details; cutting tool – cutting; insulator – creating insulation; compressor – compression and pumping of air (gas); shaft – transmission of rotational force with transfer along the axis; gear – torque transmission; housing – ensuring constant accuracy of placement of parts and mechanisms.

The main service function – the result of the joint action of basic functions.

Auxiliary (secondary) function of the object – feature (features), which is equal to, develops and clarifies the main function.

Auxiliary function (functions) also provides implementation of the main function. Secondary functions are the features (aesthetic, environmental, ergonomic and others) through which the consumer buys this object.

An auxiliary function of the machine is safe and convenient operation; shaft – orientation of the parts it carries; housing – together with the lids to create a closed space.

Many products have several features (properties) at the same time, so they have a large number of functions.

The assignment of a function to the main and auxiliary ones depends on the object of analysis according to the degree of hierarchy of the system.

Thus, for cars the function "develop the power of the drive" is auxiliary, but if the object of analysis is the engine, then for it this function is the main.

The formulation of functions requires the division of the object into independent elements, as they are the material carriers of functions.

The most specified and clearly formulated set of functions, for which TS (machine) is intended, is called the functional (operational) purpose of TS (machine).

Each machine is created to meet a specific need or needs of a human, which is reflected in its functional purpose.

The functional purpose of the product allows to establish the functionally required level of its technical parameters and modes of operation, based on customer requirements and information on the operation of similar products, to identify the possibility of meeting these requirements and technical-economic level of design and technological solutions.

The wording of the functional purpose of the machine should contain detailed information that specifies the main function and specifies the conditions under which this function will be performed. This information should include not only qualitative but also quantitative indicators relating to specific service functions, operating conditions of the machine, etc.

During the creation of the machine, its functional purpose is documented in the form of a technical task for the design of a machine.

A systemic approach is required when formulating the functional purpose of objects. For example, a machine, being a system of interconnected parts and assembly units, is included, as an integral part, in the supersystem of manufacturing a product (action); the assembly unit, being a system of parts, enters as a subsystem into the machine; the part as a system of interconnected surfaces is included as a subsystem in the assembly unit.

Therefore, when formulating the functional purpose of the assembly unit, it is necessary to formulate and clearly imagine the functional purpose of the machine, for details − the functional purpose of the assembly unit, because knowing the requirements for the system, you can develop requirements for the subsystem.

Each part of the machine is responsible for performing certain functions arising from the main function, for the implementation of which the machine is created. Together, these functions should be reflected and specified as much as possible in the functional purpose of the part. The functional purpose of the part is realized by its surfaces, which perform certain functions.

For example, the main function of the gear (torque transmission) is realized by the ring gear and the side surfaces of the keyway of the hub. The auxiliary function of the gear wheel (base) is realized by the hole and the end face of the hub, and the side surfaces of the keyway.

Identify functions − means to determine the actions performed by the object or its components, to identify the direct or indirect result of these actions aimed at achieving pre-set goals, to solve pre-selected tasks.

The formulation of functions requires the division of the object into independent elements, as they are the material carriers of functions.

The wording of the functions should be performed following certain rules:

1. Functions are formulated as an answer to the question: "How (in what way), why is the function performed?" (Table 2.1).

2. The wording must accurately reflect the true content of the processes (actions) for which the object is intended.

3. The wording should be concise (both short and precise), if possible, consist of two words − a verb and a noun. For example, "heat the blank", "connect the parts", "write the text", "cut the allowance". If the function cannot be described succinctly, it means that there is not enough information about the object, or try to consider it in an unreasonably wide form.

4. The wording should use words that denote quantities that have dimension. For example, "heat the workpiece to a temperature of 200 °C for 6 hours", "connect the parts with a force of 30 kN", "write the text in fourteen fonts", "cut the allowance with a volume of 1 cm^3/s", etc.

5. For convenience of operation of functions they are numbered on certain features (Figure 2.3).

Many TS have several features (properties) at the same time, so they have a large number of functions.

The assignment of functions to the main and auxiliary depends on the object of analysis according to the degree of hierarchy of the system.

Thus, for the car the function "to develop drive power" is auxiliary, if the object of the analysis is an engine, then for it this function is the main.

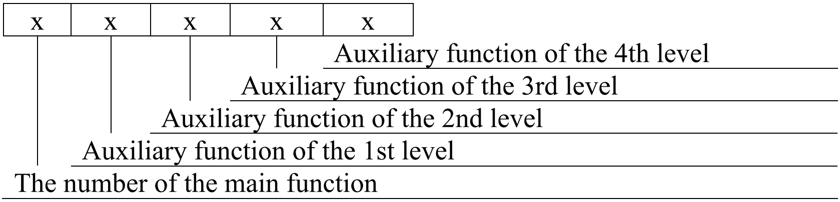

Figure 2.3 – Function's numbering scheme

According to the system approach, it is advisable to first formulate the functions of the object as a whole, and then its components.

Thus, based on the main function of the roller shock absorber (Figure 2.4) "quench the force", the functions of its parts are formulated (Table 2.2).

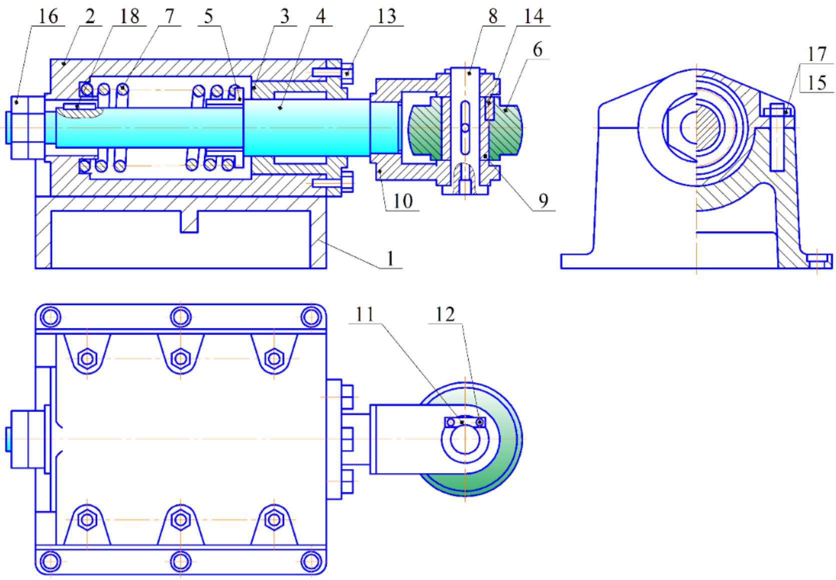

Figure 2.4 − Shock absorber roller 1 − housing; 2 − the cylinder; 3 − bushing; 4 − stock; 5 − bushing; 6 − roller; 7 − spring; 8 − axis; 9 − sleeve; 10 − fork; 11 − plate; 12 − screw M6; 13 − screw M6; 14 − screw M6; 15 − nut M8; 16 − nut M20; 17 − hairpin M8; 18 − key 10x8x22

Table 2.1 – Functions of some elements of machines

Element	Example	Description
Node	Lathe support	Creates a coordinate system for manipulating the tool in the workspace
	Gear transmission	Converts rotational speed
	Damper	Quenches oscillations
Element	Example	Description
		Create a closed space
		Perceive the load
		Quench vibrations
	Shaft	Transmits rotational forces with transfer along the axis
		Orients the parts in the assembly unit
		Gives details of rotating motion
	Bed, frame	Coordinates the main nodes and mechanisms (in some cases directs their movement)
	Gear	Transmits rotation force
		Decreases (increases) the number of revolutions
	Lever	Transmits power to connected parts
		Moves parts at a specified speed
		Fixes the position of parts
	Spline, pin	Prevents scrolling
		Orients the detail
	Crankshaft	Converts translational motion into rotational motion or vice versa
		Orients details
	Casing, shell, cover	Divides, separates from the environment, prevents, protects
	Connecting rod	Transmits motion
	Example	Description
	Bearing	Connects the shaft to the housing with the possibility of rotation
		Transmits effort to the body
		Orients the shaft
	Surface	Directs, limits, creates a point of contact
Elements of detail	Gear tooth	Transmits clutch force
	Shaft slots	Direct the axial displacement
		Transmit rotation
	Protrusion, thrust	Restricts movement

Table 2.2 – The main and auxiliary functions of the shock absorber parts

Object detail	The main function	Auxiliary function
1 Corps	F_1 Ensuring the accuracy of the permanent location of parts. Perceive the load	F_{11} Ensuring the desired position of the shock absorber on the conveyor frame
		F_{11} Cylinder base
2 Cylinder	F_{12} Ensuring a stable location of the sleeve 3 and the rod 4	F_{1201} Orientation of the rod 4 relative to the housing
3 Bushing	F_{13} Rod 4 orientation	F_{1301} Ensuring the longitudinal movement of the rod 4
4 Stock	F_{14} Orientation of the fork 10	F_{1401} Transmission of forces from the fork to the spring 7
5 Bushing	F_{15} Centring of the spring 7	F_{1501} Perception of axial forces
6 Roller	F_{16} Direction of loads without sliding friction	F_{1601} Transmission of forces on an axis
7 Spring	F_{17} Absorption of forces	F_{1701} Perception of power
		F_{1702} Return to the initial position of the rod 4
8 Axis	F_{18} Orientation of the sleeve 9	F_{1801} Lubricant supply
9 Bushing	F_{19} Transmit the force with the orientation of the roller 6 in the radial position	F_{1901} Ease of rotation of the roller 6
		F_{1902} Power transmission from the roller 6 to the axis 8
10 Fork	F_{20} Orientation of the axis 8 in the radial and axial directions	F_{2001} Power transmission from the axis 8 of the rod 4

The main function of TP machining F is the manufacture of parts in the right quantity and quality.

Based on the fact that the technological process is part of the production process, which contains targeted actions to change and determine the state of the subject of labour, we can distinguish the following two main functions:

F_{01} – Change the characteristics of the original workpiece;

F_{02} – Identify changes in characteristics.

Auxiliary functions to the first main F_{01} are:

F_{11} – Install the workpiece;

F_{12} – Resize;

F_{13} – Change the shape;

F_{14} – Change the relative position of the surfaces;

F_{15} – Change the surface quality.

Auxiliary functions of the second main function F02 are:

F_{21} – Identify size changes;

F_{22} – Identify shape changes;

F_{23} – Determine the relative location of the surfaces;

F_{24} – Identify changes in surface quality.

Functions F_{11} – F_{15}, F_{21} – F_{24} are auxiliary of the 1st order.

The operation is a complete part of the technological process, which is performed in one workplace without a break in time. Therefore, the functions of the operation are the functions of the technological process relative to the treated surfaces. These functions are second-order auxiliaries.

Thus, to the function F_{11} ---------► F_{1101} … F_{110n}

to the function F_{12} ----------------► F_{1201} … F_{120n}

to the function F_{21} ----------------► F_{2101} … F_{210n}

to the function F_{22} ----------------► F_{2201} … F_{220n}

to the function F_{23} ----------------► F_{2301} … F_{230n}

To perform some functions of the 2nd order, auxiliary functions of the third order are required.

Thus, for the function F_{1101} … F_{110n} these are the functions:

to base the workpiece – F_{11011} … F_{110n1},

to fix the workpiece – F_{11022} … F_{110n2}

For some functions there are functions of the fourth and higher orders.

The allocation of functions requires some professional training. It is not always possible to articulate them at once. This requires a good knowledge of the essence of the object being studied, as well as certain skills in wording. If the function cannot be clearly and concisely stated, it serves as a signal that the employee should deepen the preparatory work, after which return to the formulation (Figure 2.5).

The logical-graphical representation of the composition and relationship of the functions of the object, obtained by their formulation, is a functional model that allows to reveal not only all the essential connections in the object, but also allows to proceed to estimates of the significance of each function and its relative importance for the object as a whole, and then to determine the allowable limits on the cost of functions.

The significance of functions is determined by an expert method with appropriate mathematical processing of the results. The functional structure

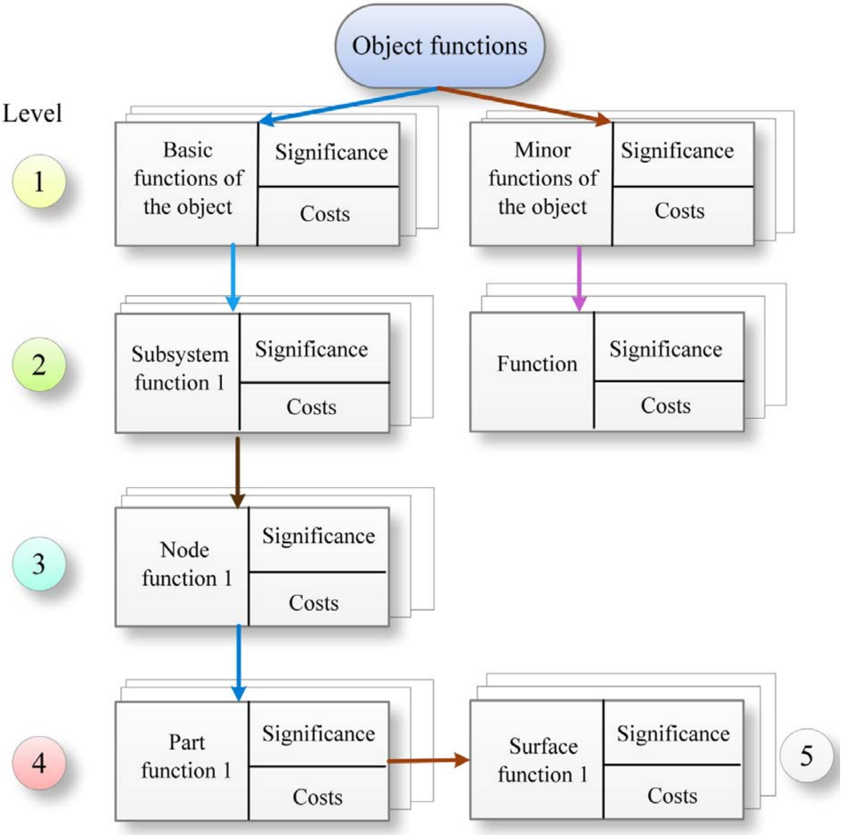

Figure 2.5 – Functional model of an object

of a design object is an ordered set of all its functions and the relationship between them can be obtained by formulating the external functions of the object, their parameters and numerical values. Then, sequentially dividing each object function into components and then dividing each of the component functions into smaller ones, blow the functional model of the object in the form of a hierarchical graph with fragmentation of functions to the desired level of decomposition, i.e., those for which it is easy to choose structural elements, which are necessary for their implementation

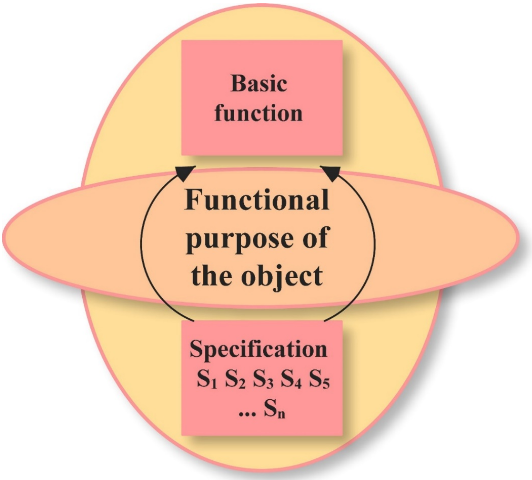

Figure 2.6 – Block diagram of the service function of the technical object

$$F = (F_{111}, F_{112}, F_{121}, F_{122}, F_{211}, F_{221}, F_{222}, F_{223}, F_{231}, F_{311}, F_{312}, F_{321}),$$

where F_{nij} – simple function of the lowest level of decomposition.

Each function has its own index, which reflects the belonging to a certain level of the structure of the object and the sequence number.

The tree of functions of the technical object has the form of a graph, the vertices of which reflect the functions of different levels of complexity, and the connections − the relationship of subordination between them (Figure 2.6).

2.2.2. Technical design

Each technical system (machine) is a set of parts, connections, mechanisms and nodes that are its components, connected by different types of connections (dimensional, kinematic, dynamic, mechanical, etc.).

Each part is a system of surfaces connected to each other and to the surfaces of other parts by functional and dimensional connections.

The machine is built by connecting parts. Parts are assembled in the assembly process to form assembly units.

Each machine, as well as its separate mechanism, carries out the functional (service) purpose by means of a number of the surfaces belonging to its details. During the operation of the machine, various **connections** (dimensional, kinematic, dynamic, mechanical, etc.) arise and operate between its surfaces, as well as connections of the properties of the materials from which the machine parts are made.

The connections of the surfaces of the parts are complex and multifaceted. Some of them (for example, dynamic) arise only in the course of work of the car. Connections of both the first and second types are laid in the machine in the process of its construction.

All the necessary types of connections in the machine are created using parts that have certain geometric shapes, sizes and relative positions and which are made of certain materials.

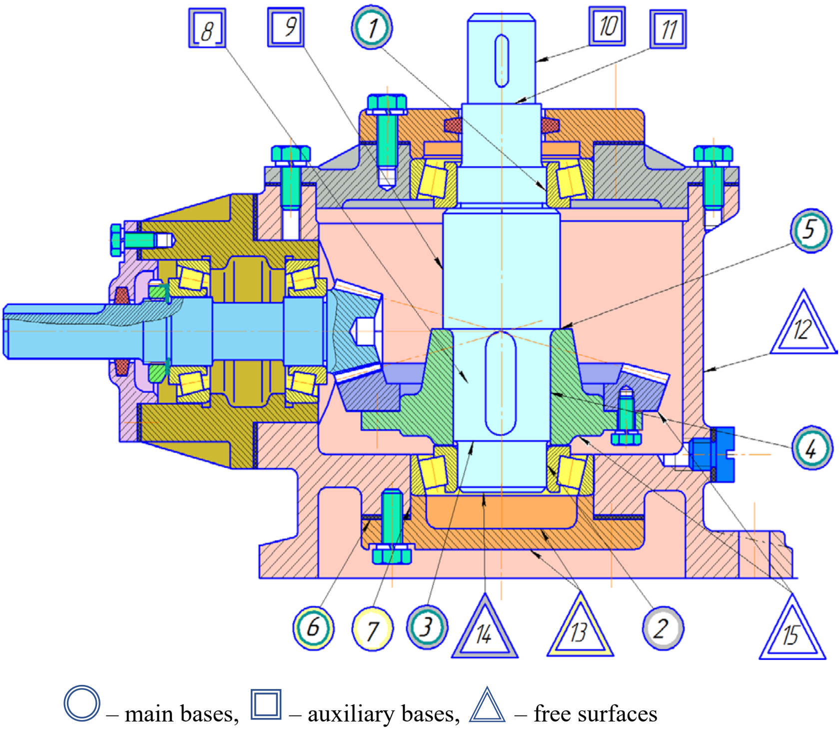

Figure 2.7 – Types of surfaces of a reducer and its details

According to the functions performed by different surfaces of parts in the machine, they can be divided into 4 types: **executive surfaces, main and auxiliary bases, free surfaces**.

Executive surfaces (ES) – these are the surfaces, or combinations thereof, by means of which the machine (CU, part) performs its functional purpose.

For example, a single-stage bevel gear (Figure 2.7) is designed to transmit transformed rotation and torque at right angle. Accordingly, its executive surfaces are the input A and output B keyway shafts and involute surfaces of bevel gears that work together.

2.3. Dimensional analysis of technical systems

During the operation of the technical system (machine) between its surfaces there are dimensional, kinematic, dynamic, electrical, magnetic, optical, hydraulic, pneumatic, chemical, temporal and other connections. In addition, there are connections between the properties of the materials from which the parts are made.

It is important that all types of connections are laid in TS in the process of its creation in the form of dimensional connections (stating the sizes, distances, relative turns, the form, roughness of surfaces of details, and also the distances and turns defining relative position. parts) and in the form of connections of materials from which the parts are to be made.

2.3.1. The essence of dimensional analysis

The quality of the machine, its productivity and efficiency in operation are mainly determined by the accuracy of geometric characteristics.

It is based on the analysis of dimensional relationships first between the parts of mechanisms and nodes, and then within each part. The analysis of dimensional connections of the machine is called dimensional analysis.

Dimensional analysis – it is a set of calculation and analytical procedures for identifying and constructing dimensional relationships of the machine or its part, rational sizing, assignment of appropriate tolerances and their coordination, as well as evaluation of the results obtained.

Dimensional analysis allows to reasonably set the dimensional and accuracy characteristics of the elements of the machine and economically provide the desired quality of manufactured structures.

Dimensional analysis of the design of a machine in the development of technology is necessary to understand the relationship of parts and assembly units that create the machine; determine methods for achieving the required accuracy of the machine; analyse the correctness of affixing dimensions and tolerances in the drawings of the machine and make, if necessary, changes in size and tolerances in accordance with the planned technological methods and means of ensuring the required accuracy of various parameters of the machine, develop a sequence of assembly of the machine and its assembly units; choose technological bases of parts, etc.

Typically, for any, predetermined on the drawings of the system of dimensions in the process of development of the technological process or its implementation, bases for applying the dimensions can be replaced in accordance with the accepted method of processing and technological bases. However, it should be remembered that any change without sizing, if necessary, to maintain the tolerances specified in the drawing, inevitably leads to a decrease in processing tolerances.

The dimensions of the parts (as well as the parts themselves) in the assembled product are interrelated. These relationships are defined by the dimensional relationships that create the assembly dimensional chains that arise during the assembly of the machine. The latter are provided with the corresponding sizes of the details resulting from the technological dimensional chains arising at realization of TP of machining.

The relative location of the surfaces of the parts can be set in the drawings of different size systems, thus providing different accuracy.

The methods of sizing affect the manufacturability of the structure, because between the sizing and the sequence of processing of workpieces there is a certain relationship.

The method of relative coordination of surfaces also largely determines the type of cutting tool, measuring instruments, device design and, mainly, the ability to work on well-established equipment.

The affixing of dimensions and tolerances in the drawing of the part should reflect the requirements for this part, based on its functional purpose and provide the ability to manufacture the part with simple technological methods by which the requirements for it can be met.

Observance of the first condition is provided by detection of dimensional connections of surfaces of a detail on the basis of the dimensional analysis

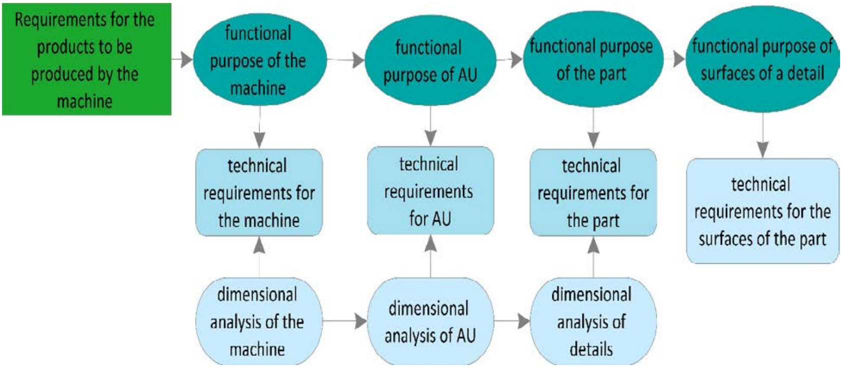

Figure 2.8 – The scheme of formation of technical requirements to their components

of the mechanism, the second – by the correct choice of tolerances for the sizes entering into assembly dimensional chains thanks to the correct choice of a method of achievement of accuracy of a closing section (Figure 2.8).

The correct functioning of TS and its components is ensured, first of all, by the existing relative position or movement of executive surfaces, which are described by a number of geometrical characteristics, such as dimensions, relative rotations (parallelism, perpendicular) and relative location of surfaces or their elements (alignment, symmetry, etc.). In an assembled product, the parts are interconnected and interdependent. Deviations in the dimensions, shape and location of the axes or surfaces of any of the parts cause deviations of the shapes or deviations in the location of other parts of the assembly unit. These deviations, in sum, in a certain way affect the quality characteristics of the product.

2.3.2. Formation of dimensional connections of the technical system

The formation of dimensional connections of the technical system includes four stages:

1) identification of the types of connections through which the TS (machine) performs its functional purpose;

2) identification of executive surfaces between which it is necessary to make the necessary connections;

3) transformation of connections of executive surfaces into dimensional and connections of properties of materials;

4) determining the accuracy of the connections of the executive surfaces of the machine.

The required **types of connections** of executive surfaces of the technical system follow from its functional purpose.

For example, a technical system − a horizontal milling machine is designed for machining planes and grooves. In order to process the workpiece parts, it is necessary:

a) specify the relative position of the workpiece and the cutting tool;

b) carry out the relative movement of the workpiece and the cutting tool;

c) create the effort required to carry out the process of cutting the material.

This way, dimensional, kinematic and dynamic connections must be created in the machine.

Different types of connections can be used to implement the required connections of the executive surfaces. For example, the feed of the workpiece relative to the cutter can be created mechanically or hydraulically, i.e. mechanical or hydraulic connections can be used.

The type and shape of TS executive surfaces are determined based on its functional purpose and the type and nature of the required connections. Successful detection of executive surfaces largely depends on how deeply their functions have been detected.

For this, the device must have a flat mounting and a flat base guide. Hence the simplest solution arises: a flat table with rectangular grooves.

The position of the cutting tool in its rotational motion relative to the workpiece is most accurately provided by the conical surface.

In order for the created TS to carry out the process of manufacturing products of the required quality, it is necessary to **move from the parameters** of its functional purpose to the parameters of the connections of its executive surfaces. This transition is mainly through calculations.

Analytical relationships between the parameters of the functional purpose and the parameters of the connections of the executive surfaces are expressed by equations of the type

$$\mathrm{P_i} = f\left(x_{1_i}, x_{2_i}, \ldots, x_{n_i}\right),$$

where $\mathrm{P_i}$ – parameter of the functional purpose of the machine;

x_i – parameter of one of the types of connections of the executive surfaces of the machine, on which the value Pi depends.

Since the original equation is one and the n is unknown, it can be solved only by selecting the values of arguments (x_i). Selection can give an infinite number of solutions, but this must be tolerated, because there is no other way to solve the original equation. Some reduction in the number of decisions can be achieved if to take into account the current rules of argument values (if any), the experience of solving similar problems in the past, as well as the economic side of the case.

The required accuracy of the connections of the executive surfaces of the TS (machine) is determined by its functional purpose and is set:

– as a result of theoretical researches of physical essence of the phenomena accompanying work of TS, and carrying out of the corresponding calculations;

– based on experiments on prototypes of TS (machines);

– as a result of studying the experience of operation of TS (machines) of a similar type;

– based on the experience of the person who establishes the accuracy of the connections of the executive surfaces TS (machine).

It is best if the tolerances of the connection parameters of the executive surfaces of the machine were set by calculation. The initial data for such calculation are tolerances of characteristics of quality of production for the release of which the machine is created.

The calculation plan is the same as the calculation of the nominal values of the parameters: first make the transition in the tolerances of the product and its manufacturing process to the connections of the executive surfaces, and then the transition in the tolerances from one type of connection of the executive surfaces of the machine to others. The calculation is based on the original equations, which generally express the functional dependence of the parameter "P" on the arguments x_1, x_2, …, x_n.

The original equation is often nonlinear. Therefore, it is linearized, usually by decomposition into a Taylor series, limited to members of the first order.

To establish the norms of geometric accuracy of the machine, corresponding to its functional purpose, it is necessary to limit the tolerances of the parameters of the relative position and direction of movement of its executive surfaces.

In general, the relationship of parameter tolerance T_{P_i} with argument tolerances T_{x_j} can be expressed by the dependence

$$T_{P_i} \geq \sqrt{\sum_{i=1}^{n} \left(\frac{\partial P_i}{\partial x_{ij}} \right)^2 T_{x_{ij}}^2}$$

$$T_{P_j} = f\left(T_{x_{1i}}, T_{x_{2i}}, \ldots, T_{x_{mi}}\right)$$

The calculation of parameter tolerances is reduced to setting the values of arguments' tolerances T_{x_j} and the coordinates of the midpoints of the tolerance fields $\varnothing_{0_{x_{ji}}}$, arising from the functional purpose of the machine. As with the calculation of denominations, the **selection of values** T_{x_j} and $\varnothing_{0_{x_{ji}}}$, accordingly satisfying the values T_{P_j} and $\varnothing_{0_{\Pi_i}}$ is the only way to solve the problem, since for n unknowns there is only one equation of their connection.

The found values of tolerances of indicators of accuracy of relative position and movement of executive surfaces of the machine are divided into two parts: the **tolerance on operation wearing** of the machine during its operation – T_{op}, and **tolerance on manufacture** of the machine T_{mn} (Figure 2.9).

When dividing the tolerance into two parts, there is a contradiction between the consumer and the manufacturer of the machine, because it is advantageous for everyone to get most of the total tolerance. If most of the tolerance is allocated for operation, the quality of the machine will be higher, but at the same time the cost of its manufacture will increase. If most of the total tolerance is used by the manufacturer, it is likely that after a short operation the machine will fail. Therefore, the problem of dividing the tolerances into two parts can be solved correctly only as a result of technical and economic calculation. So far, there are no reliable methods for dividing the tolerance into two parts.

The parts of the tolerances left for the manufacture of the machine are called the tolerances for the acceptance of the finished machine. These tolerances also have to be divided into two parts: the assembly and adjustment of the machine and the manufacture of parts. This distribution of tolerances should also be made on the basis of the lowest cost of manufacturing the machine.

The technical system can be represented as a set of coordinate systems built on the basis of parts with overhead dimensional connections.

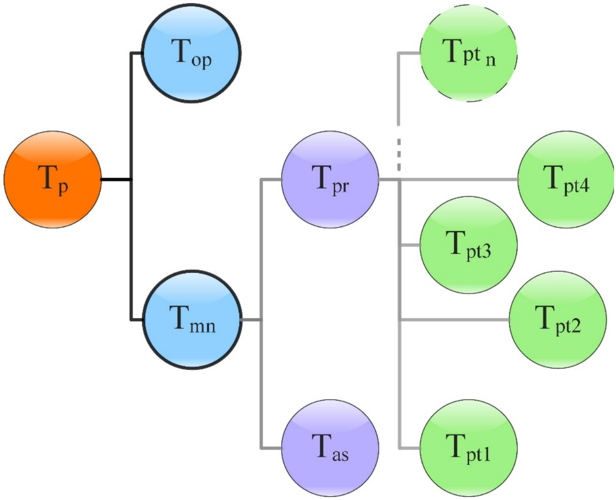

Figure 2.9 – The scheme of distribution of tolerances of quality indicators:

T_p – tolerance parameter, T_{op} – tolerance on operation wear of the machine during its operation, T_{mn} – tolerance on manufacture of the machine, T_{mn} – tolerance on production of the unit; T_{as} – tolerance on assembly of the part; $T_{pt\ n}$ – tolerance on production of the n-th part

Connection of details is carried out through combination of the main bases of the connected detail and auxiliary bases of a detail (details) to which it connects.

That is, the connection of parts can be considered as a combination of coordinate systems of their main and auxiliary bases.

The relative position of two parts (assembly units) is determined by six geometric parameters: three linear coordinates (A, B, C) offset of the origin XYZ coordinate system of the main bases of the connected part in the system XYZ auxiliary bases of the base part (or CU) and three angles (φ, γ, θ) of rotations of system XYZ concerning coordinate axes of system XYZ (Figure 2.10).

Accordingly, the position of the part in the XYZ coordinate system in the general case can be determined by the radius – vector $\bar{r}$ and a matrix M of angles of rotations:

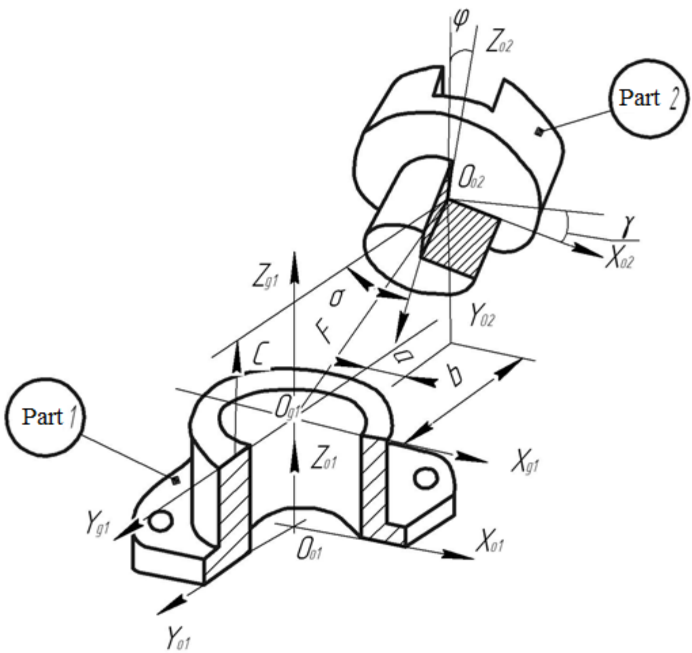

Figure 2.10 – The relative position of the two parts.
Notation indices: O – coordinate system of the main base of the part;
g – the same auxiliary bases; 1,2 – part numbers

$$\bar{r} = \begin{matrix} A \\ B \\ C \end{matrix}\ ; \ M = M(x,\varphi) \bullet M(y,\gamma) \bullet M(z,\theta),$$

where M(x, φ), M(y, γ), M(z, θ) – the rotation matrix of the coordinate system of the connecting part, respectively, at an angle φ around the axis OX, at an angle γ around the axis OY, at an angle θ around the axis OZ of the coordinate systems of the base part.

The relative position of the details of the technical system (machines, CU, mechanisms) determine the dimensional connections of the coordinate systems of their main and auxiliary bases (Figure 2.11).

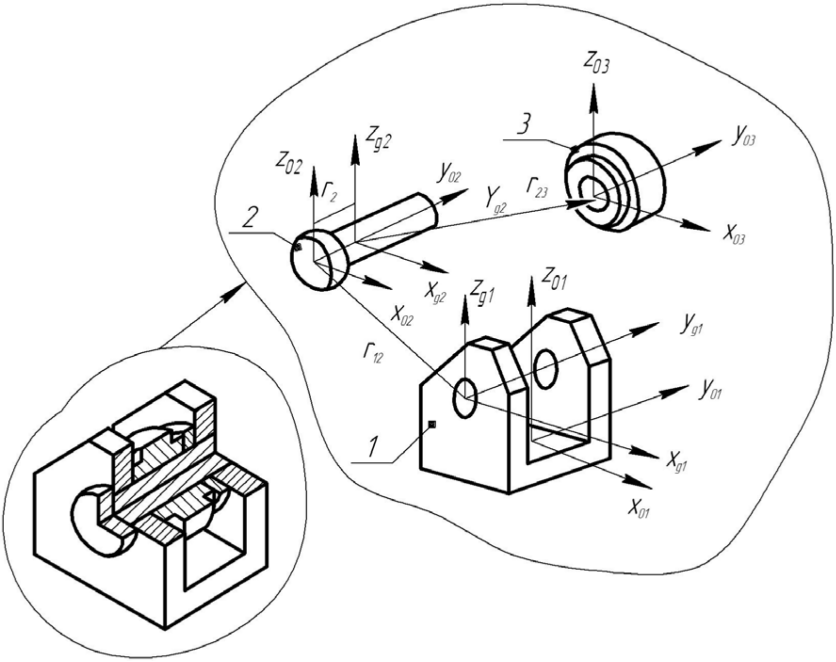

Figure 2.11 – Coordinate systems of the main and auxiliary bases of parts of the assembly unit: 1 – housing; 2 – axis; 3 – roller

Permissible upper and lower limit deviations can be expressed in matrices

$$\Delta_{\text{бг}} = (\Delta_{\text{бa}}, \Delta_{\text{бб}}, \Delta_{\text{бc}}, \Delta_{\text{б}\beta}, \Delta_{\text{б}\gamma}, \Delta_{\text{б}\mu});$$

$$\Delta_{\text{нг}} = (\Delta_{\text{нa}}, \Delta_{\text{нб}}, \Delta_{\text{нc}}, \Delta_{\text{н}\beta}, \Delta_{\text{н}\gamma}, \Delta_{\text{н}\mu}).$$

The difference between these deviations is nothing but the tolerance field of the vector $\overline{r}$

$$Tr = \Delta_{\text{бг}} - \Delta_{\text{нг}}.$$

Ensuring the required accuracy of the connections of the executive surfaces is to move from the tolerances on the parameters of their accuracy to the tolerances of the parameters of the component sections of the connections.

The dimensional connections of the machine and its components form a system of spatial dimensional chains.

In general, dimensional relationships can be represented as a system of equations:

$$\begin{cases} \bar{R} = \sum_{i=1}^{m} M_i \overline{r_j} \\ M_j = \prod_{j=1}^{i} M'_{i-j+1}, i = 1, 2, \ldots, m, \end{cases}$$

where $\bar{R}$ – radius vector of the closing section of the dimensional spatial chain;

$\bar{r}_j$ – radii vectors of sections constituents;

M_i – rotation matrix of the i-th coordinate system;

M'_{i-j+1} – rotation matrix (i-j+1) coordinate system relative to the conjugate (i-j) -th coordinate system;

m – the number of components of the spatial dimensional chain.

As can be seen in the system of equations, the linear size of the closing section of the spatial chain depends on the linear and angular dimensions of the constituent sections, and the angular size – only on the angular dimensions.

Equation for calculating tolerances of angular dimensions:

$$T_{j,k} = \sum_{n=1}^{i} C_n \left(\left| T_{\varphi_{i-n+1}} \right| + \left| T_{\psi_{i-n+1}} \right| + \left| T_{\theta_{i-n+1}} \right| \right),$$

where $C_n = \prod_{j=1}^{n} M'_{n-j+1}$;

$T_{\varphi_{i-n+1}}$; $T_{\psi_{i-n+1}}$; $T_{\theta_{i-n+1}}$ – errors of angles of successive turns (i-n+1)-th coordinate system.

If i=m, then the design tolerance of the angular dimensions of the closing link is determined from the equation:

$$T_{\Delta,k} = \sum_{n=1}^{m} C_n T_{n,k},$$

where $T_{n,k}$ – design tolerance of angular dimensions of all components of the spatial dimensional chain.

The fundamental difference between the calculation of the spatial dimensional chain from the linear and angular is that the denominations and tolerances of linear (x, y, z) and angular (φ, ψ, θ) parameters are considered as interrelated values.

Any detail is a spatial body bounded by a set of certain surfaces (executive surfaces, main bases, auxiliary bases and free surfaces).

If to connect the OXYZ coordinate system to the main bases and to other surfaces the system $O_iX_iY_iZ_i$, then their position relative to the main bases is determined by the vector $\bar{r}$ (Figure 2.12).

$$\bar{R} = \left(A, B, C, \varphi, \psi, \theta\right),$$

where A, B, C – three parameters of the offset of the beginning of the coordinate system $O_iX_iY_iZ_i$ relative to the system $OX_0Y_0Z_0$;

φ, ψ, θ – three angles of rotation of the coordinate system $O_iX_iY_iZ_i$ relative to the system OXYZ.

The dependence of the accuracy of dimensions, the accuracy of relative rotations and the accuracy of the geometric shape of the surface of the part have the form:

$$T_{L_X} = T_a + yT_\theta + zT_\psi + h_x;$$

$$T_{L_y} = T_б + xT_\theta + zT_\varphi + h_y;$$

$$T_{L_z} = T_c + xT_\psi + zT_\varphi + h_z;$$

where T_a, $T_б$, T_c – tolerances of the coordinates of the beginning of the system of auxiliary bases OXYZ in the coordinate system of the main bases OXYZ;

$T_\varphi, T_\psi, T_\theta$ – tolerances of relative rotations of auxiliary bases;

h_x, h_y, h_z – boundary deviations of the shape of the surfaces;

x, y, z – coordinates of edge points;

$T_{L_X}, T_{L_y}, T_{L_z}$ – accuracy of distances by coordinates.

Since the quality and complexity of products is largely determined by the quality of dimensional testing of the structure, dimensional analysis is an important part and a mandatory component of technical preparation of production.

2.3.3. Functional structure of dimensional analysis

As a component of system technology, dimensional analysis must perform a set of functions.

The main function F of dimensional analysis is the minimization of costs to ensure product quality in the product life cycle.

The main function is provided by a set of basic F_i and auxiliary F_{ij} functions.

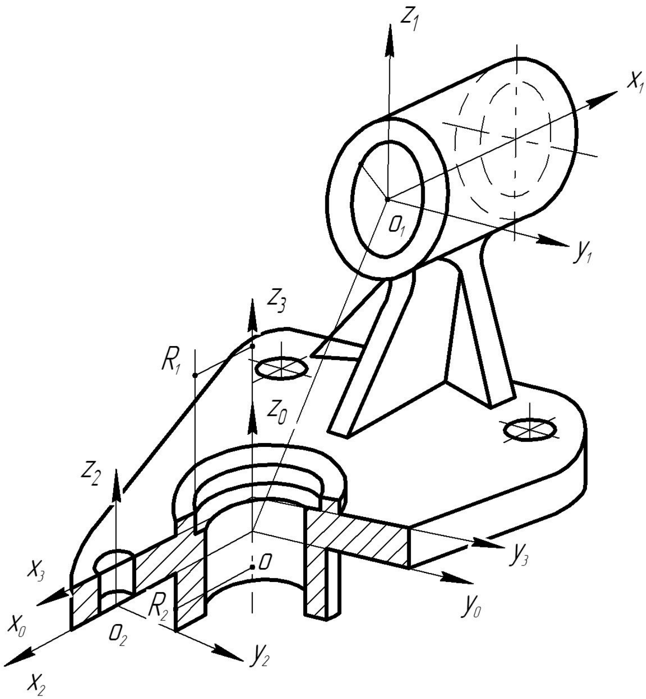

Figure 2.12 – Dimensional connections of the main and auxiliary bases of the part

F_1 – clear wording of the functional purpose;

F_{11} – detection and fixation of dimensional connections of executive surfaces;

F_{12} – appointment of the necessary and sufficient number of accuracy standards and technical requirements;

F_{13} – assigning reasonable tolerances for dimensional connections;

F_2 – detection and fixation of dimensional connections of the machine;

F_{21} – construction of dimensional diagrams of the machine, assembly units, parts;

F_{22} – definition of rational methods of achievement of accuracy of the set parameters of quality of products;

F_{23} – calculation of exact parameters of dimensional relations;

F_{24} – development of technical conditions for the machine and its components;

F_{25} – rational affixing of the sizes in working drawings of details;

F_{26} – check of collectability of assembly units and the machine;

F_{27} – forecasting the possible risk of parametric failure;

F_3 – technological support of design dimensions and technical requirements;

F_{31} – substantiation of the sequence of technological operations of machining and assembly;

F_{32} – detection and fixation of technological dimensional connections;

F_{33} – construction of dimensional diagrams of technological operations and processes;

F_{34} – calculation of operating sizes, allowances and tolerances;

F_{35} – conversion of design dimensions to technological;

F_{36} – choice of base option;

F_{37} – forecasting the possible risk of parametric failure of technological systems;

F_{38} – determination of unknown technological dimensions;

F_{39} – the choice of methods to achieve the accuracy of dimensional parameters during machining;

F_{310} – the choice of methods to achieve the accuracy of dimensional parameters during assembly;

F_{311} – determining the type of assembly by the level of interchangeability;

F_{312} – substantiation and calculation of accuracy of technological equipment;

F_{313} – determination of methods and accuracy of means of control of dimensional parameters of quality;

F_4 – ensuring compliance of design and technological dimensional connections;

F_{41} – checking the composition of products;

F_{42} – clarifying the parameters of operational dimensional relationships;

F_{43} – determination of the actual risk of parametric failures of technological systems of machining and assembly;

F_{44} – checking the compliance of the type of compilation with the level of interchangeability;

F_{45} – identification and solution of technological dimensional chains in accordance with the production tasks;

F_5 – maintaining the quality of dimensional relationships;

F_{51} – determining the type and size of transport containers;

F_{52} – determining the type and technology of canning products;

F_{53} – determination of the temperature regime of products storage;

F_{54} – determination of the sizes of cells and means of storage of products;

F_6 – using the quality of the actual size of the connections of the machine as a stimulator of its implementation;

F_{61} – determination of the main qualitative parameters of dimensional connections, important for the buyer of the product;

F_{62} – determining the level of parameters of dimensional connections relative to the performance of similar products of competitors;

F_{63} – effective advertising of the benefits of more accurate and stable dimensional product connections;

F_7 – ensuring the stability of dimensional relationships;

F_{71} – determination of numerical values of repair parameters;

F_{72} – determination of methods and means of ensuring constant accuracy of the sections of dimensional chains;

F_{73} – determination of terms of product maintenance;

F_{74} – predicting the limit values of the dimensional parameters of the product joints;

F_{75} – determination of time, methods and accuracy of means of control of actual values of functional dimensional parameters of a product;

F_8 – reengineering of dimensional connections;

F_{81} – use of parts in new machines, the accuracy of which meets the new requirements;

F_{82} – determining the accuracy of the sections of the dimensional chains of parts that need to be restored, but are suitable for use;

F_{83} – identification of parts to be disposed of.

As can be seen, dimensional analysis is available in the CALS environment as direct and indirect (not considered here) functional relationships, ensuring the accuracy of objectively existing dimensional connections of a machine, nodes and parts in solving various design and technological tasks.

Calculation of dimensional chains and their analysis is a mandatory part of the stage of preparation of production, which helps to improve quality, ensure interchangeability, reduce the complexity of products, as well as reduce the total time of the stage.

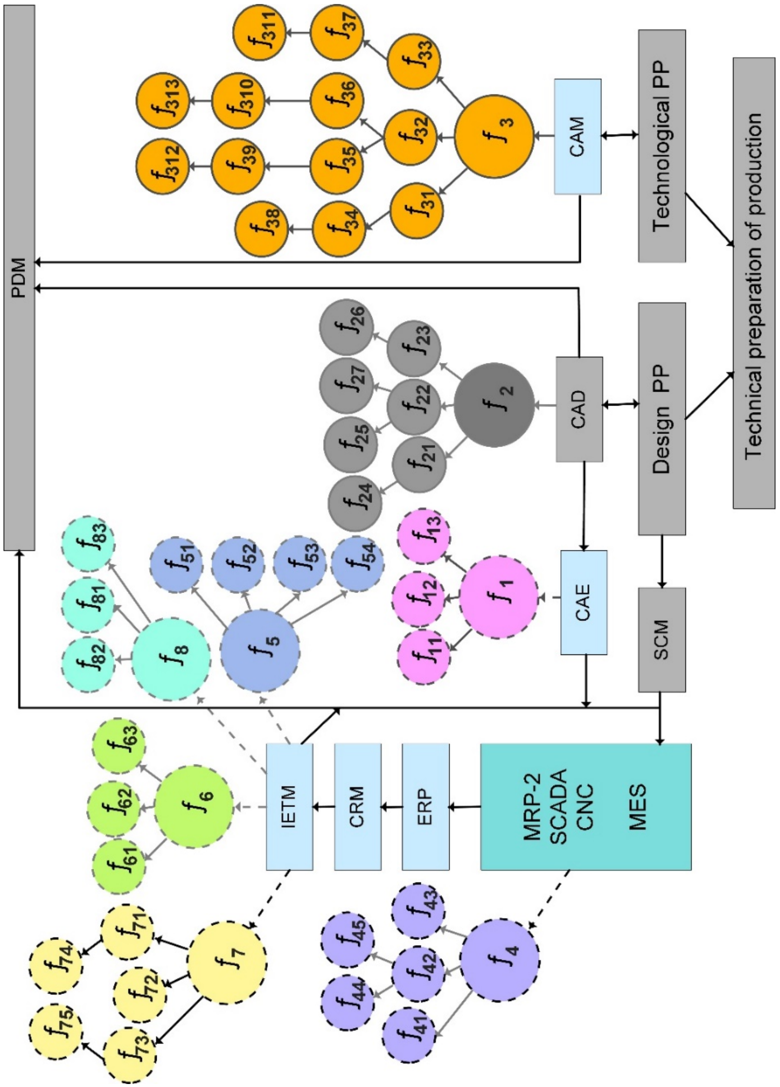

Figure 2.13 – Functions of dimensional analysis in the CALS system